Moist physics at high resolution
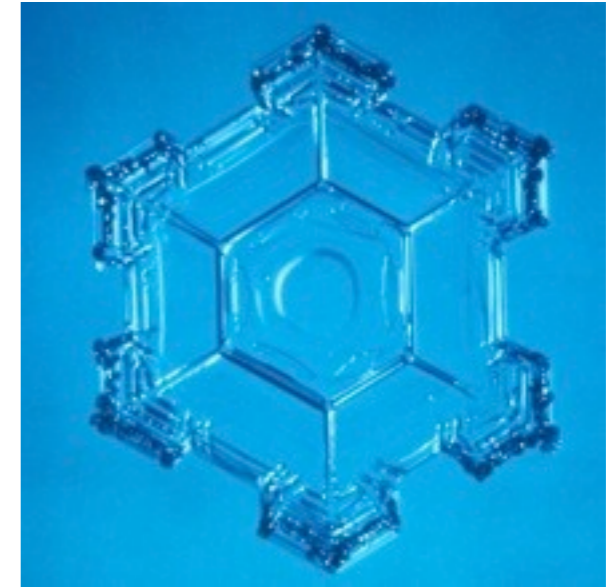
David Randall

Conventional Parameterizations

Global circulation

Cloud-scale &mesoscale processes
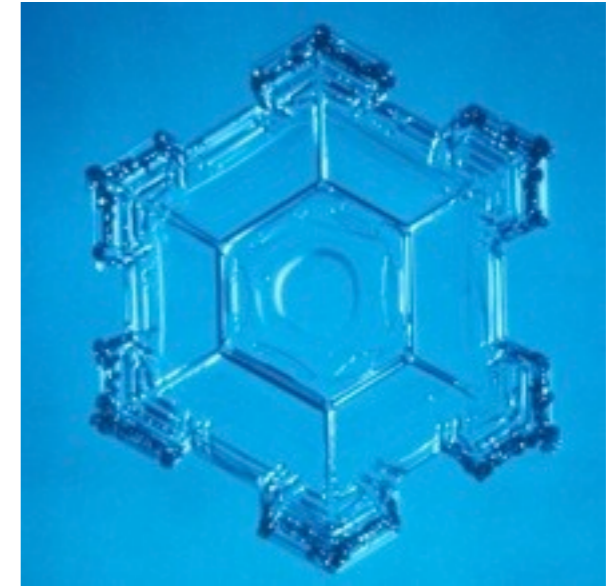

Radiation, Microphysics, Turbulence

Conventional Parameterizations

Global circulation

Cloud-scale &mesoscale processes

Radiation, Microphysics, Turbulence

Parameterized

Analogy

	Thermodynamics	Cloud Parameterization
Players	Molecules	Clouds
Volume	1 cubic cm	1 model grid column
Sample size	Trillions of molecules	Dozens to thousands of clouds
Simplifying assumptions	Point-like molecules; Inter-molecular collisions usually negligible	Small updraft area; Uniform environment; No direct interactions among clouds
Nonequilibrium effects	Brownian motion, etc.	TBD, maybe mesoscale organization

How many thunderstorms fit?

With a grid spacing of 20 km or less, we definitely do not have a statistically meaningful sample of large clouds in each grid column.

Even with a grid spacing of 200 km, the number of large clouds in a grid column is worryingly small.
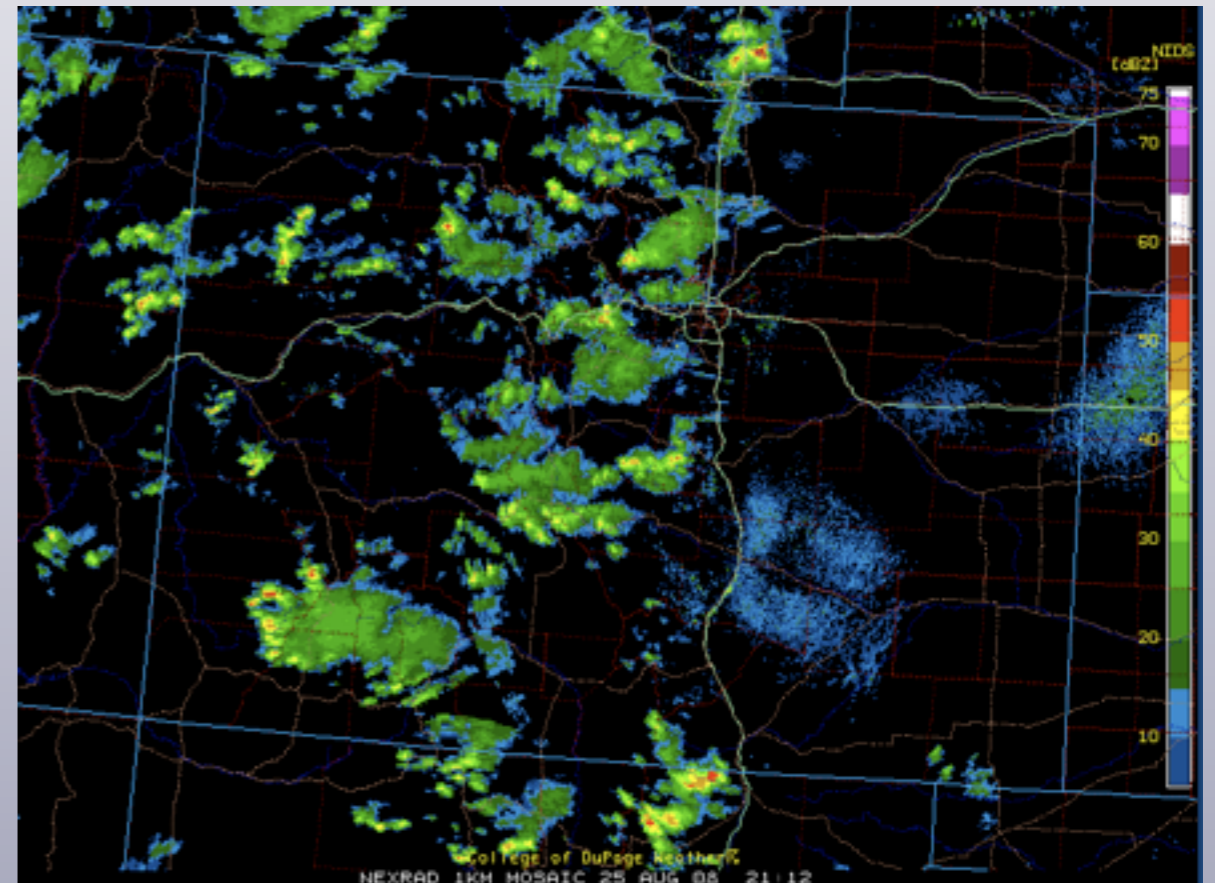
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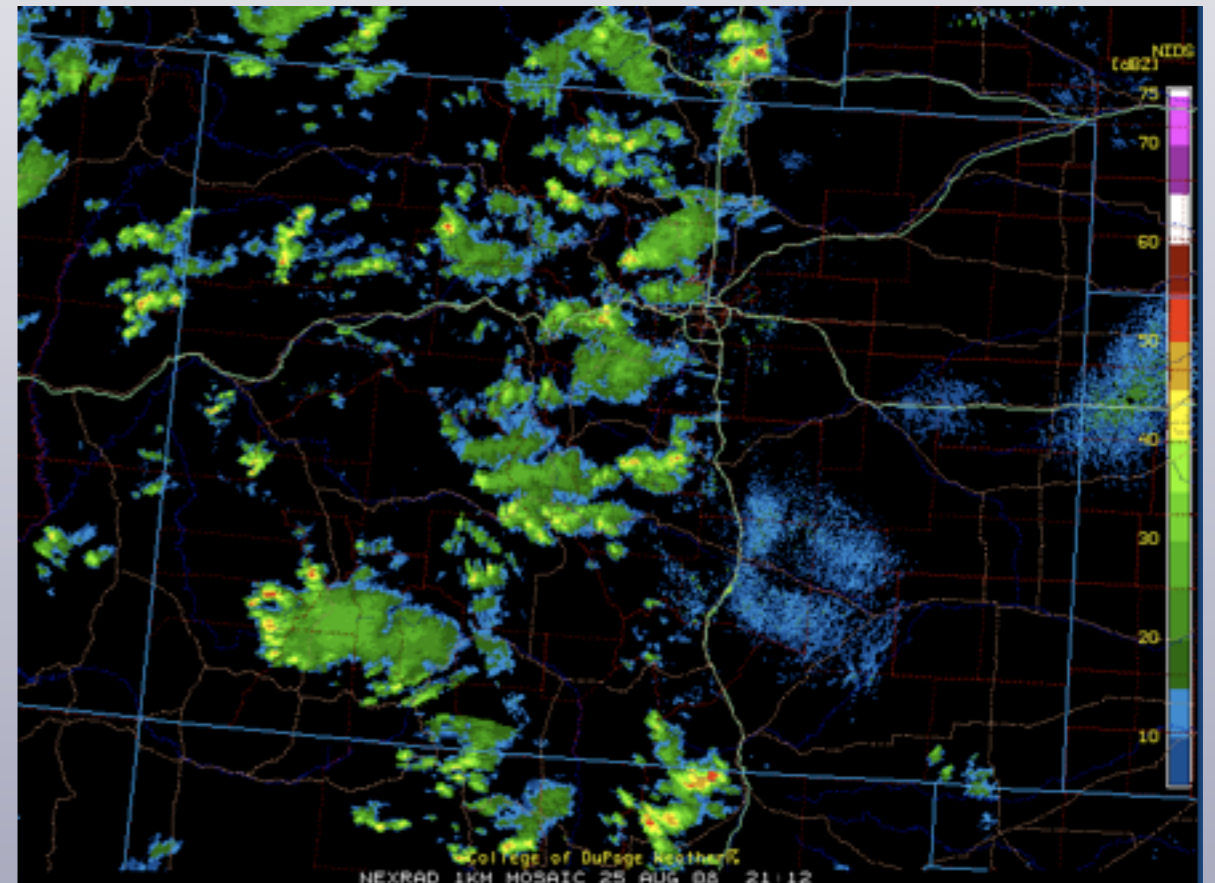
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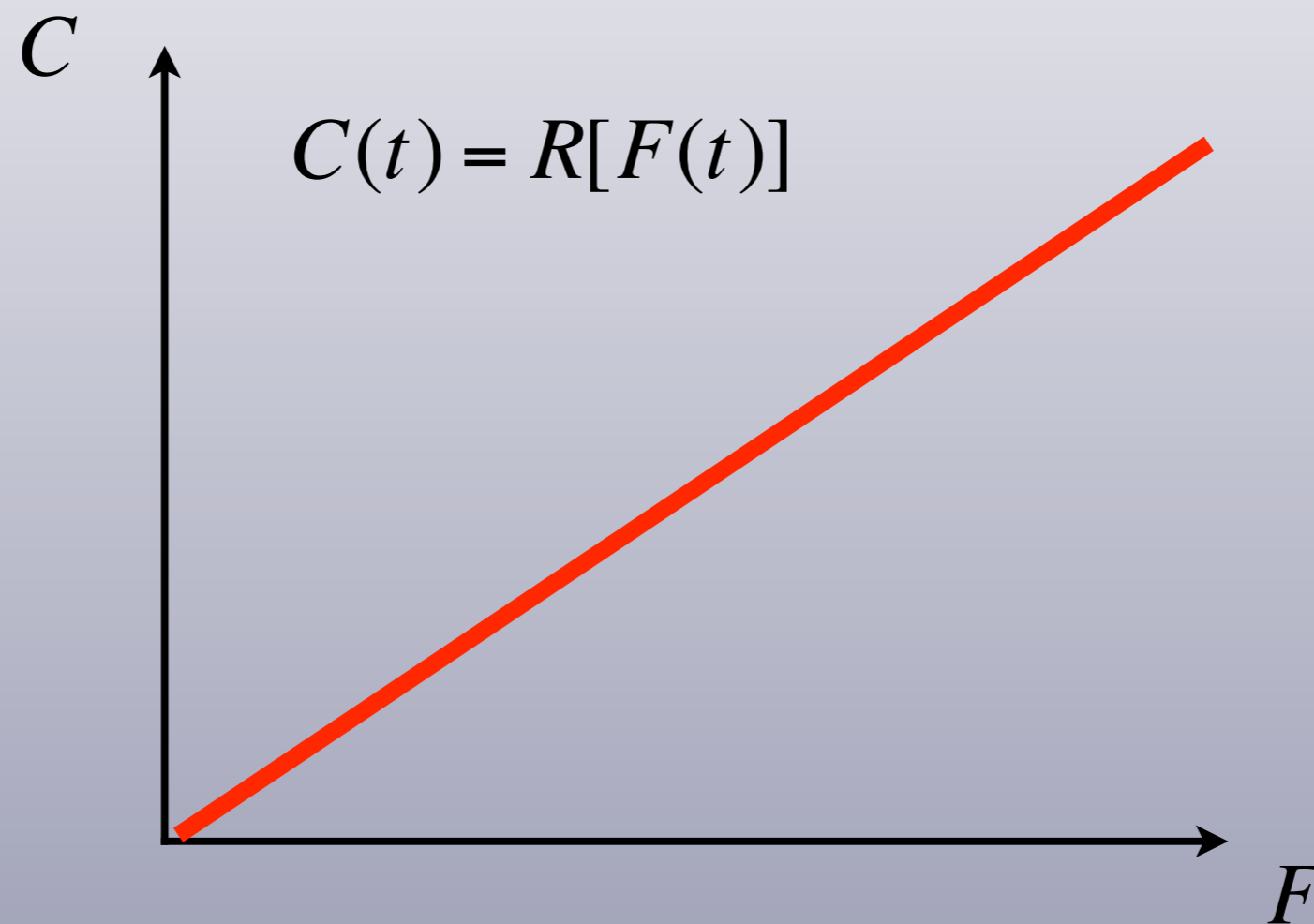

This is a fundamental issue.

Quasi-Equilibrium

"When the time scale of the large-scale forcing, is sufficiently larger than the [convective] adjustment time, ... the cumulus ensemble follows a sequence of quasi-equilibria with the current large-scale forcing. We call this ... the quasi-equilibrium assumption."

"The adjustment ... will be toward an equilibrium state ... characterized by ... balance of the cloud and large-scale terms..."
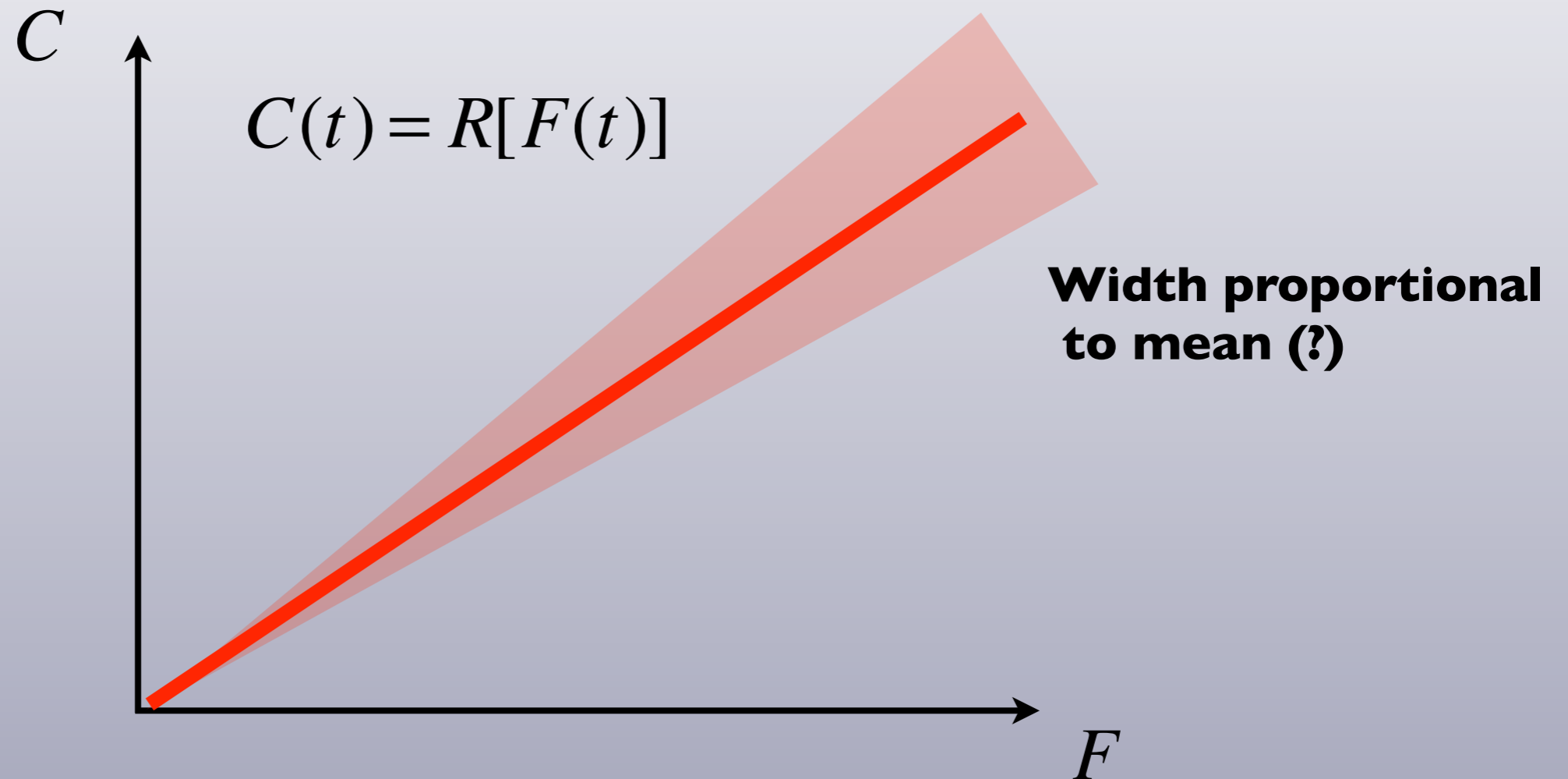
-- AS 74

Quasiequilibrium

Sample size

$$C(t) = R[F(t)]$$

Sample size

$$C(t) = R[F(t)]$$

Width proportional to mean (?)
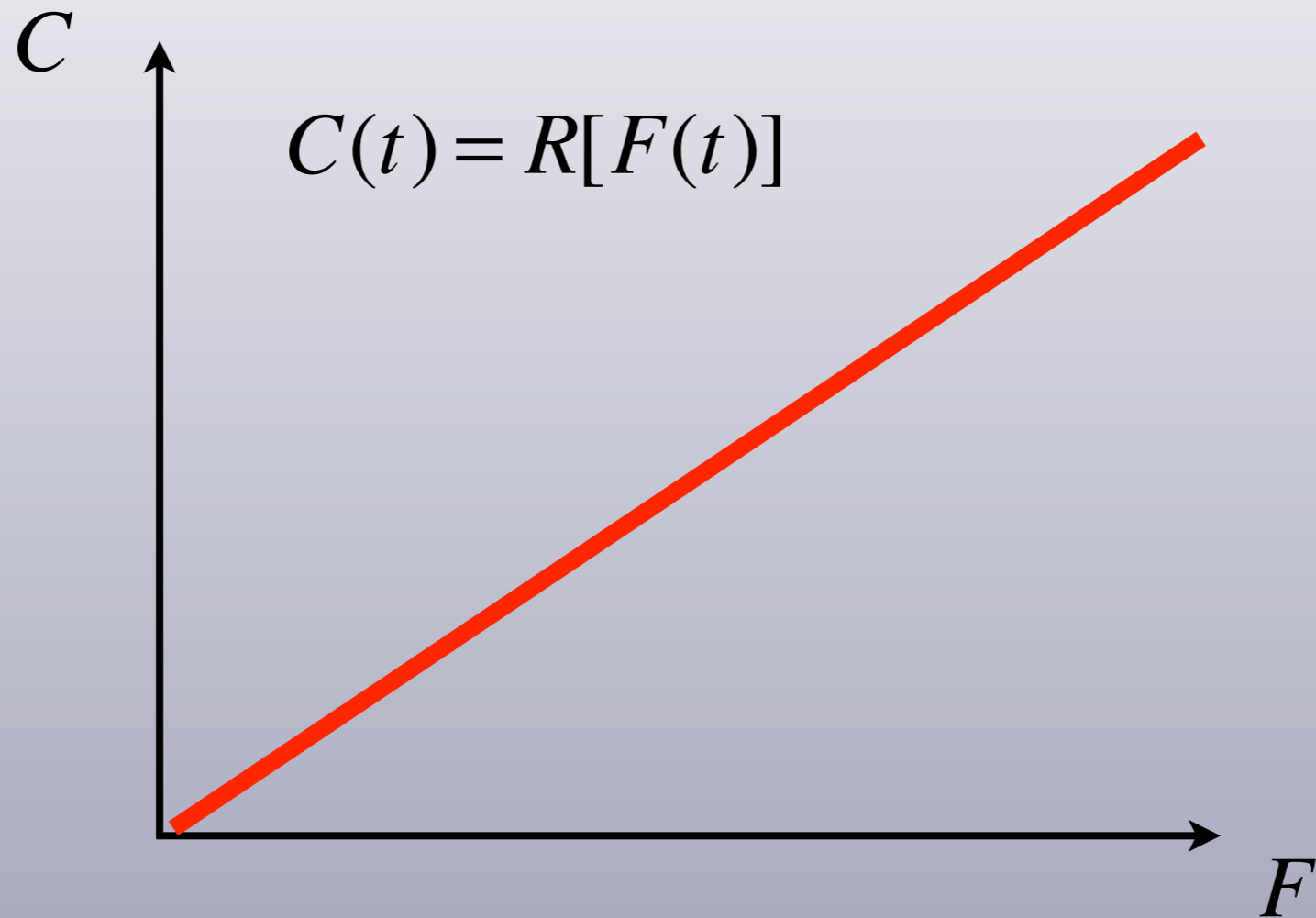
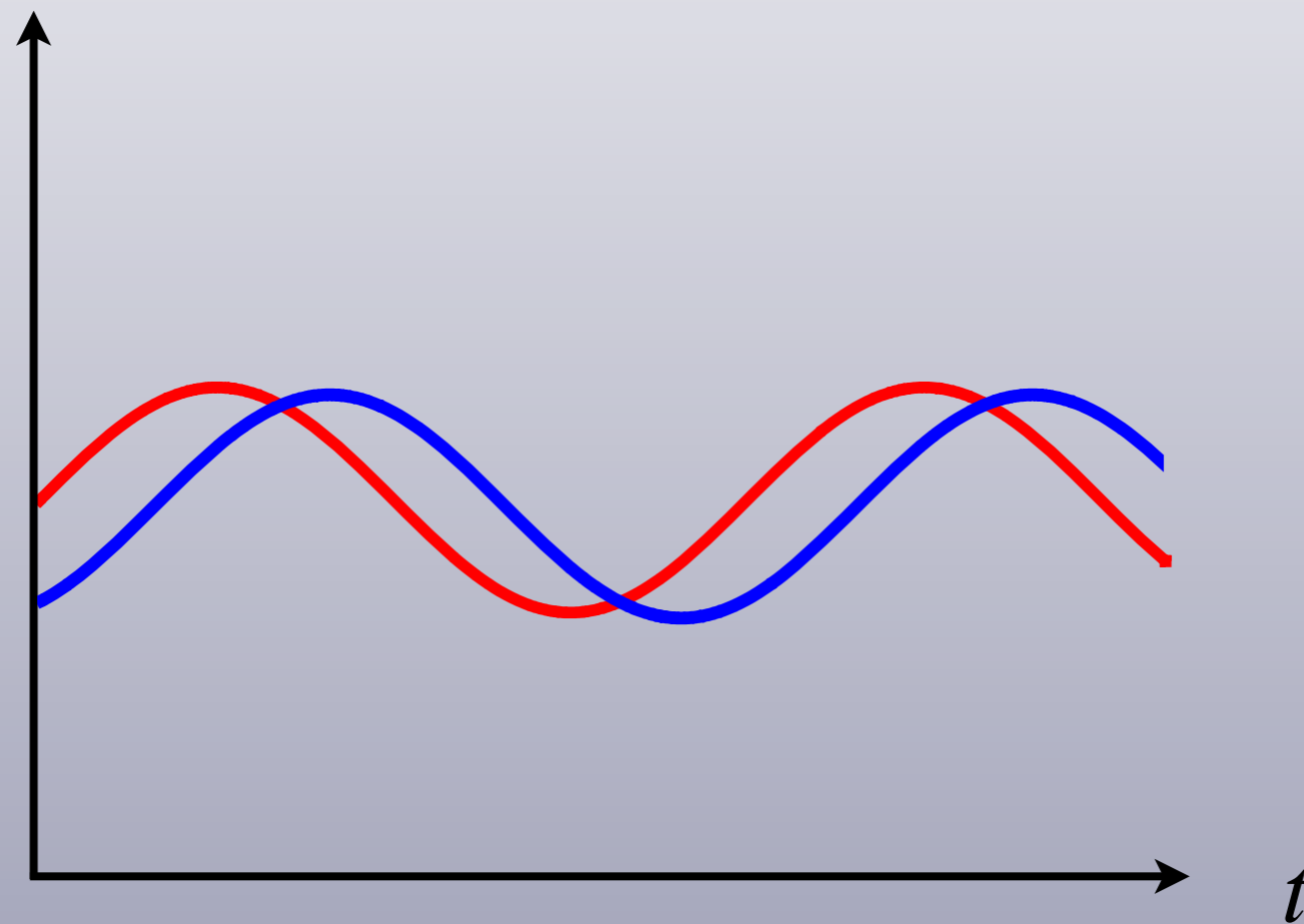**With a small sample size but slowly changing conditions, we get non-deterministic, non-equilibrium behavior.**
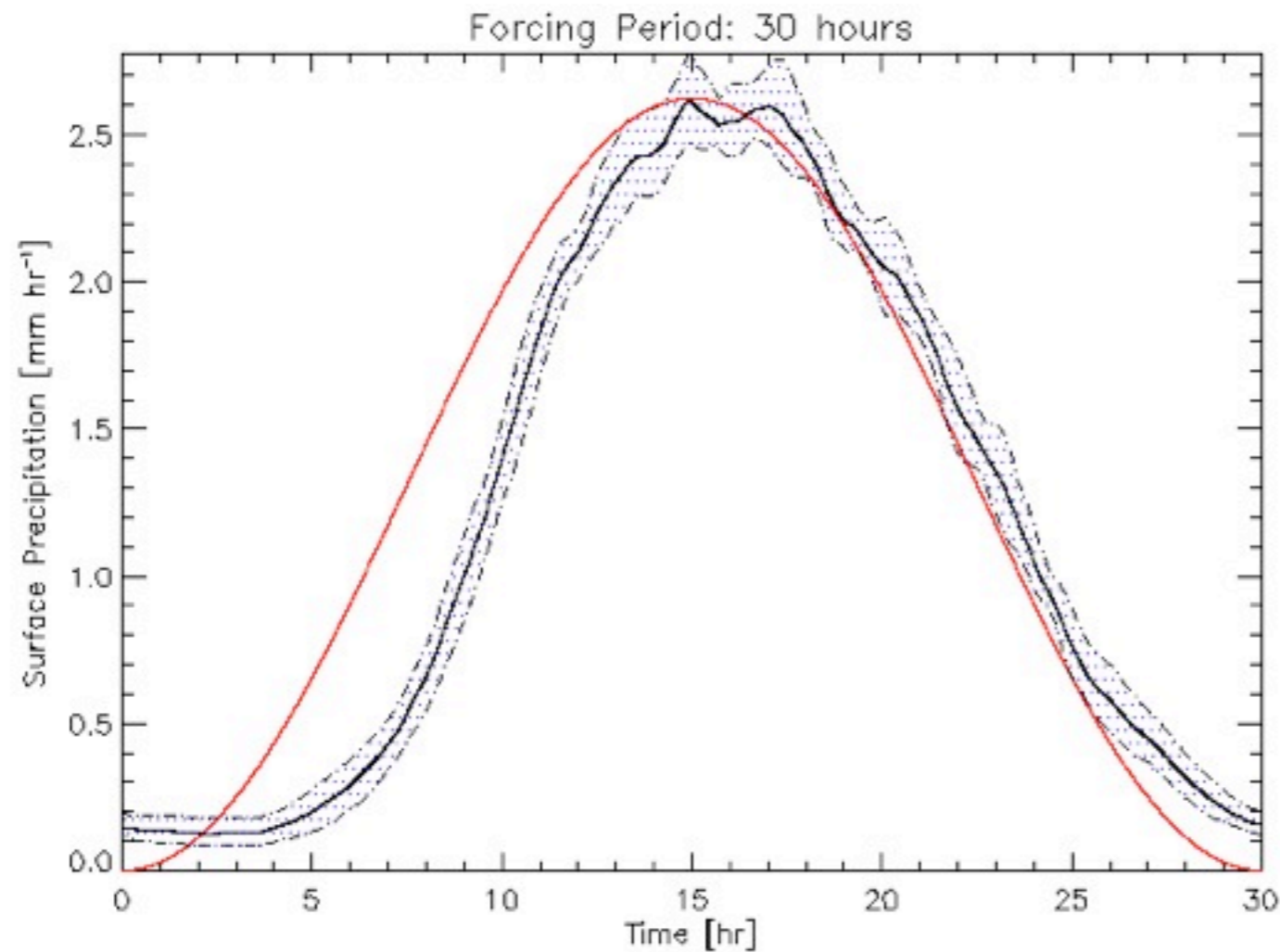
Delayed response
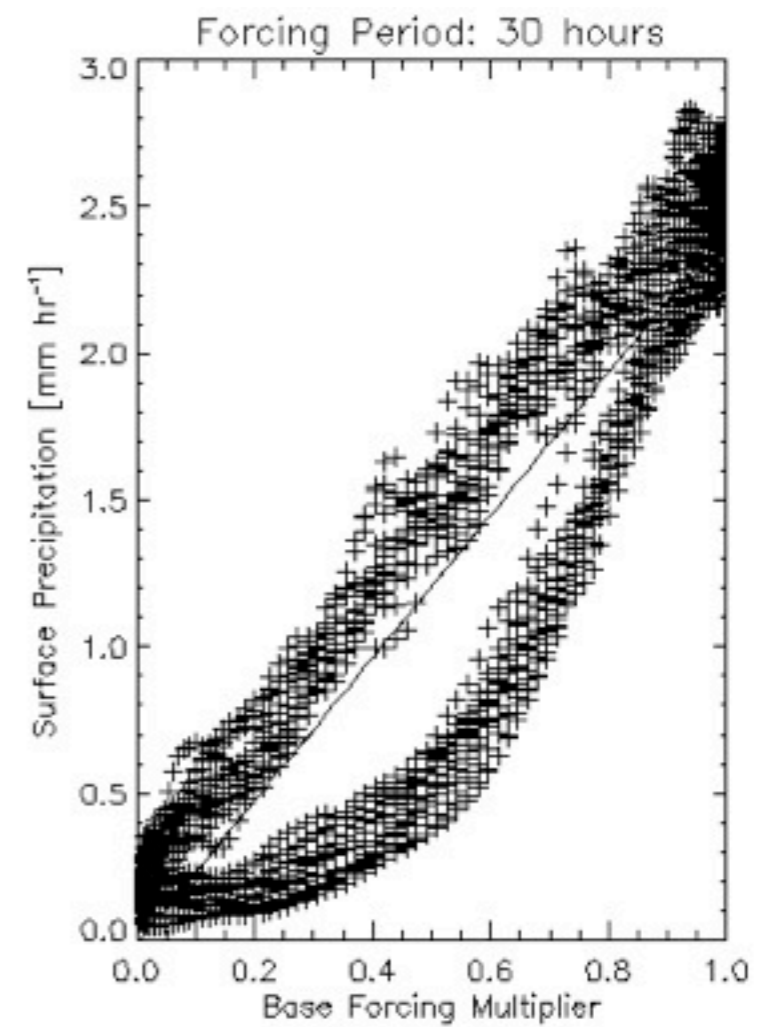
$$C(t) = R[F(t - \tau)]$$

t

With rapidly changing conditions, equilibrium is not possible (even with a large sample size), but the convection can still be deterministic.
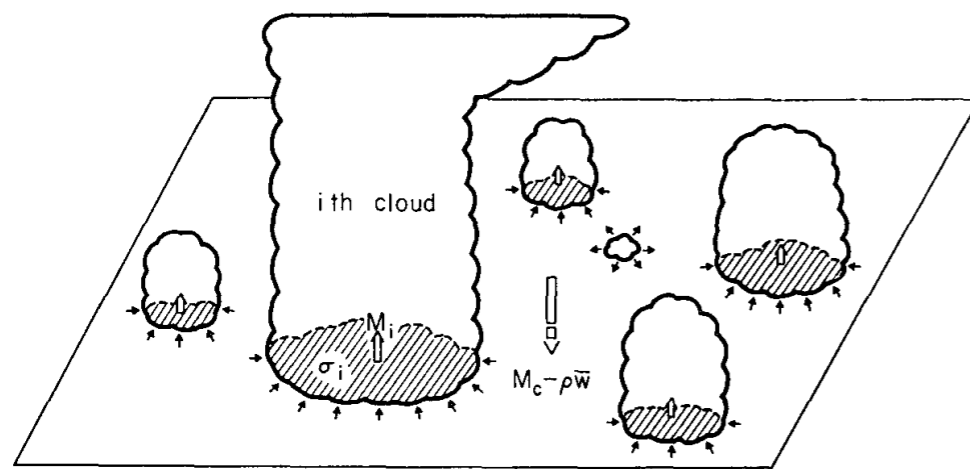
Both problems at once

Forcing Period: 30 hours

Forcing leads Precip max by: 95 minutes (5.28 % of the forcing period)

Forcing Period: 30 hours

$r^2 = 0.875$
Slope = 2.437

Slide from Todd Jones

Heating and drying
on coarse and fine meshes

GCM
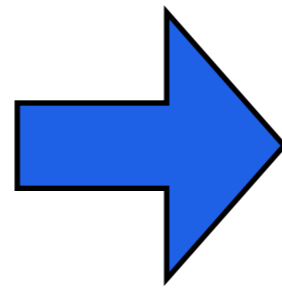
Increasing resolution

CRM

Parameterizations for low-resolution models are designed to describe the collective effects of ensembles of clouds.

Parameterizations for high-resolution models are designed to describe what happens inside individual clouds.

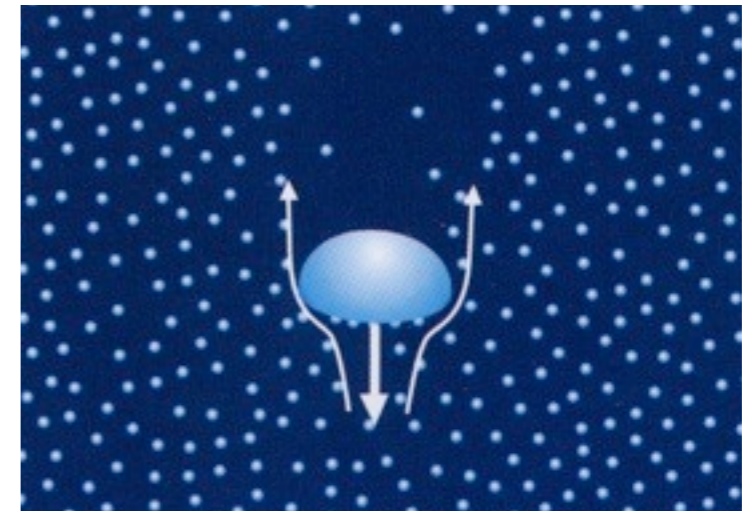# Heating and drying on coarse and fine meshes

Increasing resolution

GCM

CRM

Parameterizations for low-resolution models are designed to describe the collective effects of ensembles of clouds.

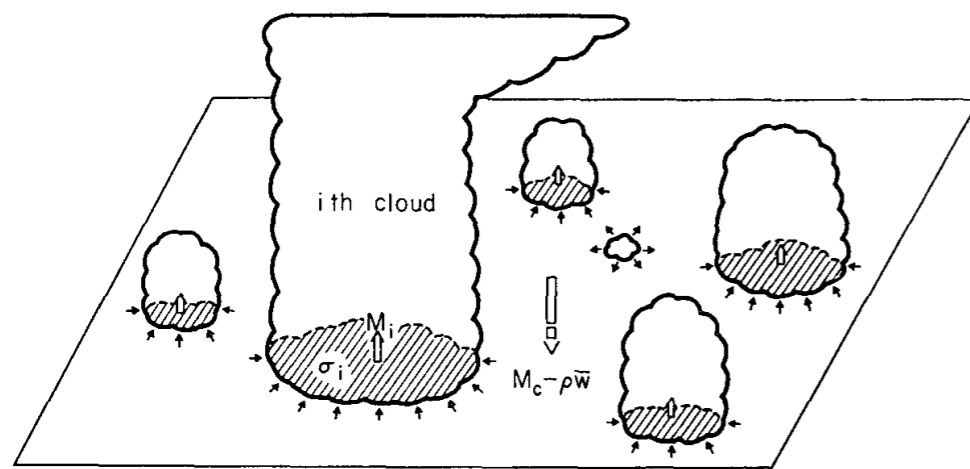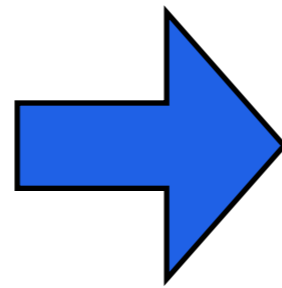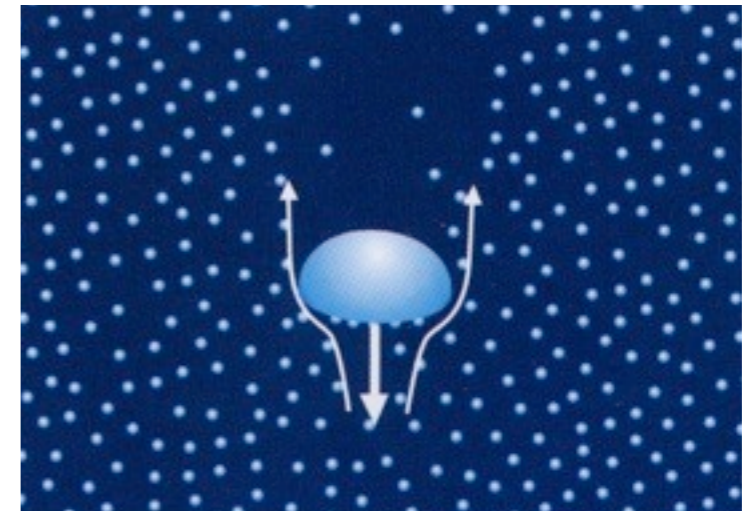**Parameterizations for high-resolution models are designed to describe what happens inside individual clouds.**

Expected values --> Individual realizations

Scale-dependence of heating & drying

$$Q_1 - \overline{Q_R} = L\overline{C} - \frac{1}{\rho}\frac{\partial}{\partial z}(\rho\overline{w's'}) - \frac{1}{\rho}\nabla_H \cdot (\rho\overline{\mathbf{v}_H's'}),$$

$$Q_2 = -L\overline{C} - \frac{1}{\rho}\frac{\partial}{\partial z}(\rho\overline{w'q_v'}) - \frac{1}{\rho}\nabla_H \cdot (\rho\overline{\mathbf{v}_H'q_v'}).$$

*These quantities are **defined** in terms of spatial averages.*

As the averaging length becomes smaller:

- **The vertical transport terms become less important. Later horizontal averaging does not change this.**

- **The horizontal transport terms become more important locally. Horizontal averaging kills them, though.**

- **The phase-change terms become dominant.**

Typical vertical profiles of the apparent moist static energy source due to convective activity
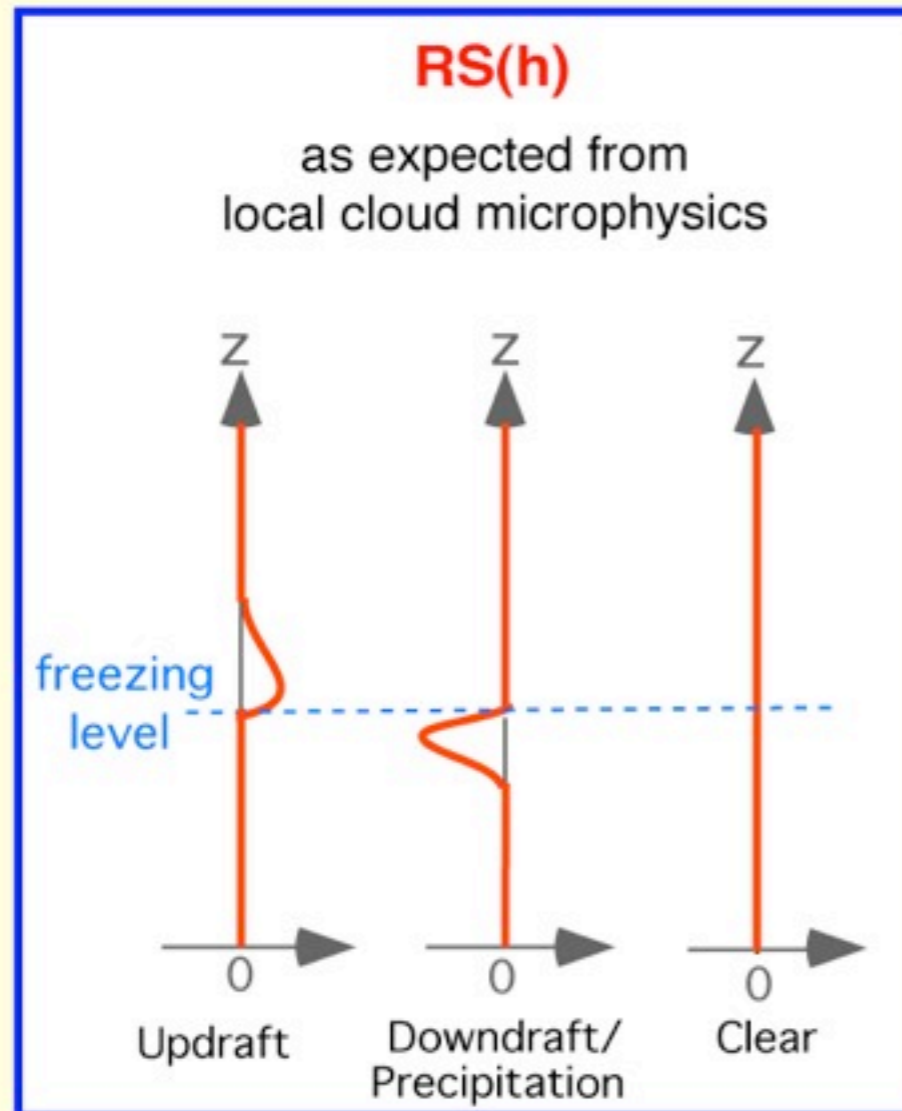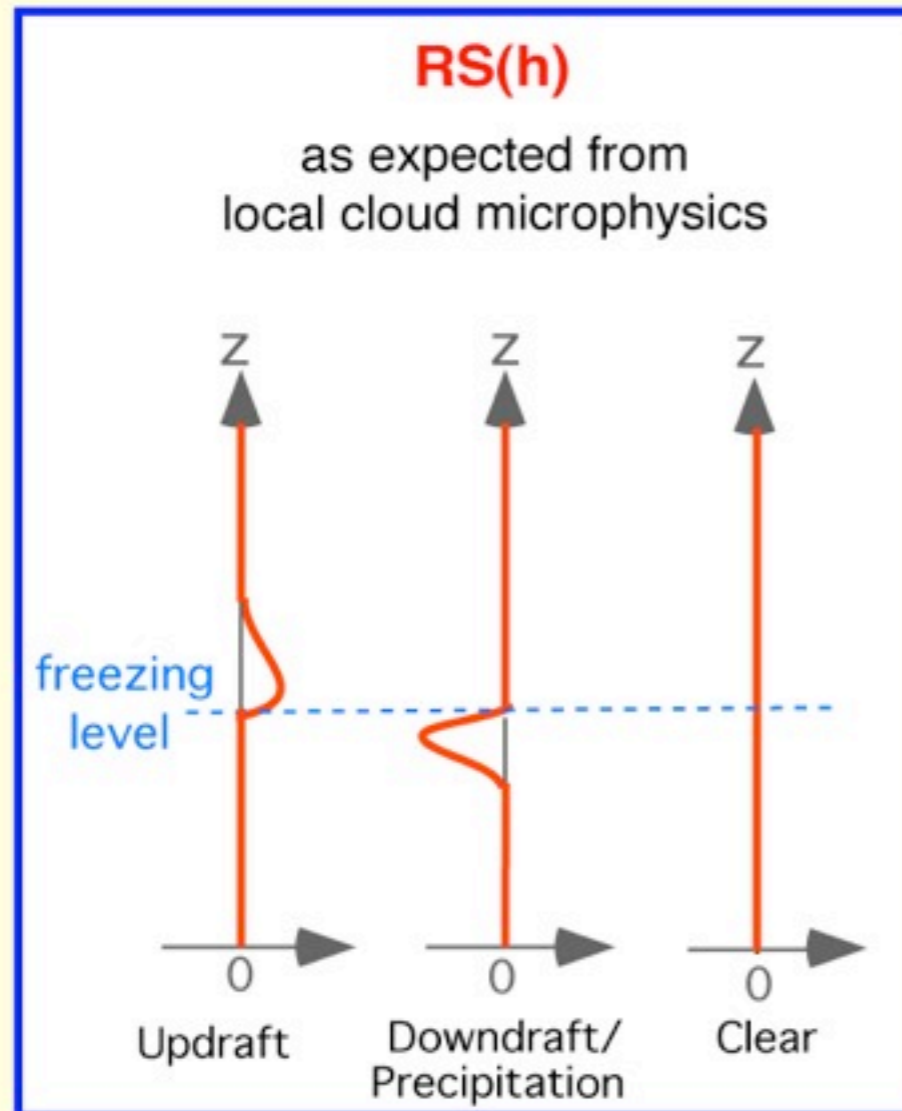
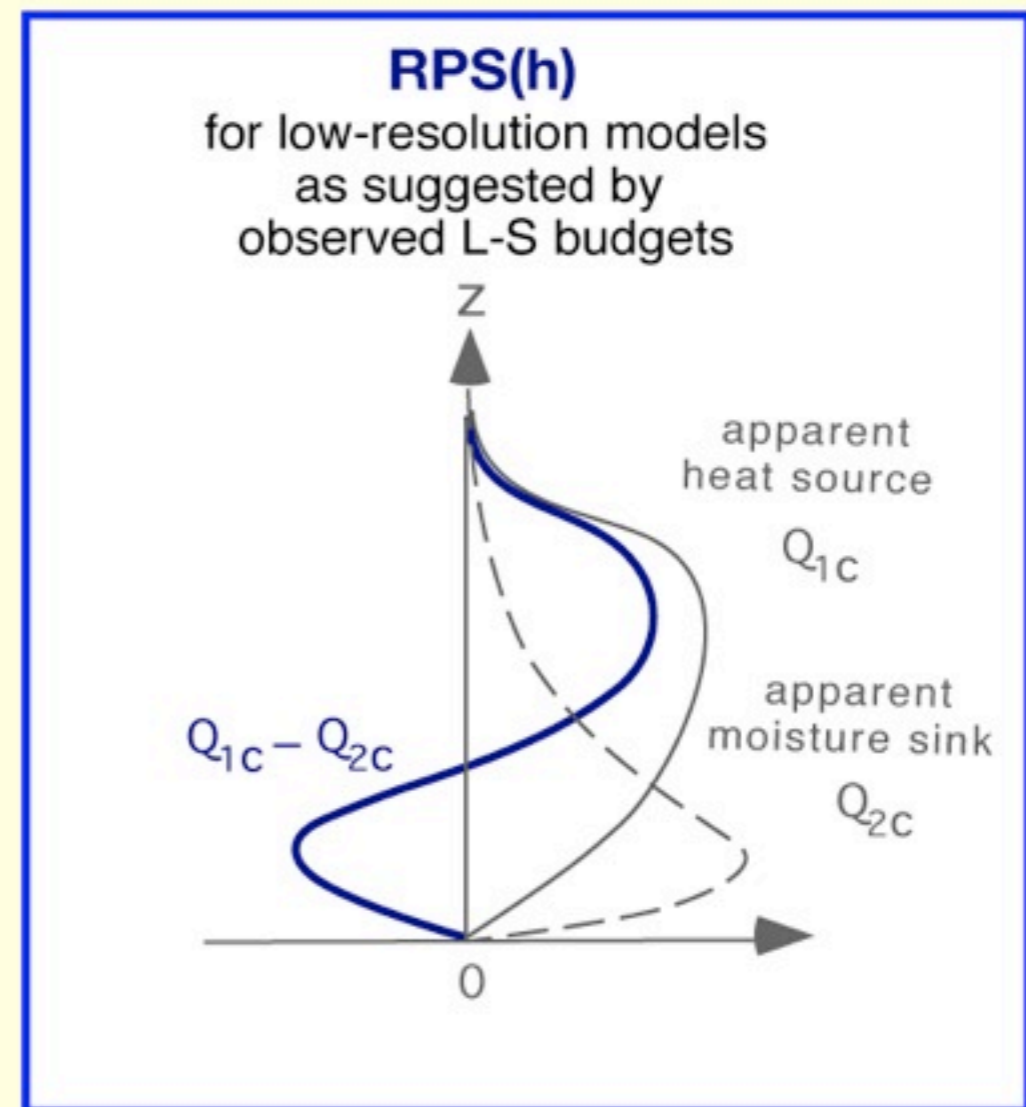**Fine scale**

Average over a larger area
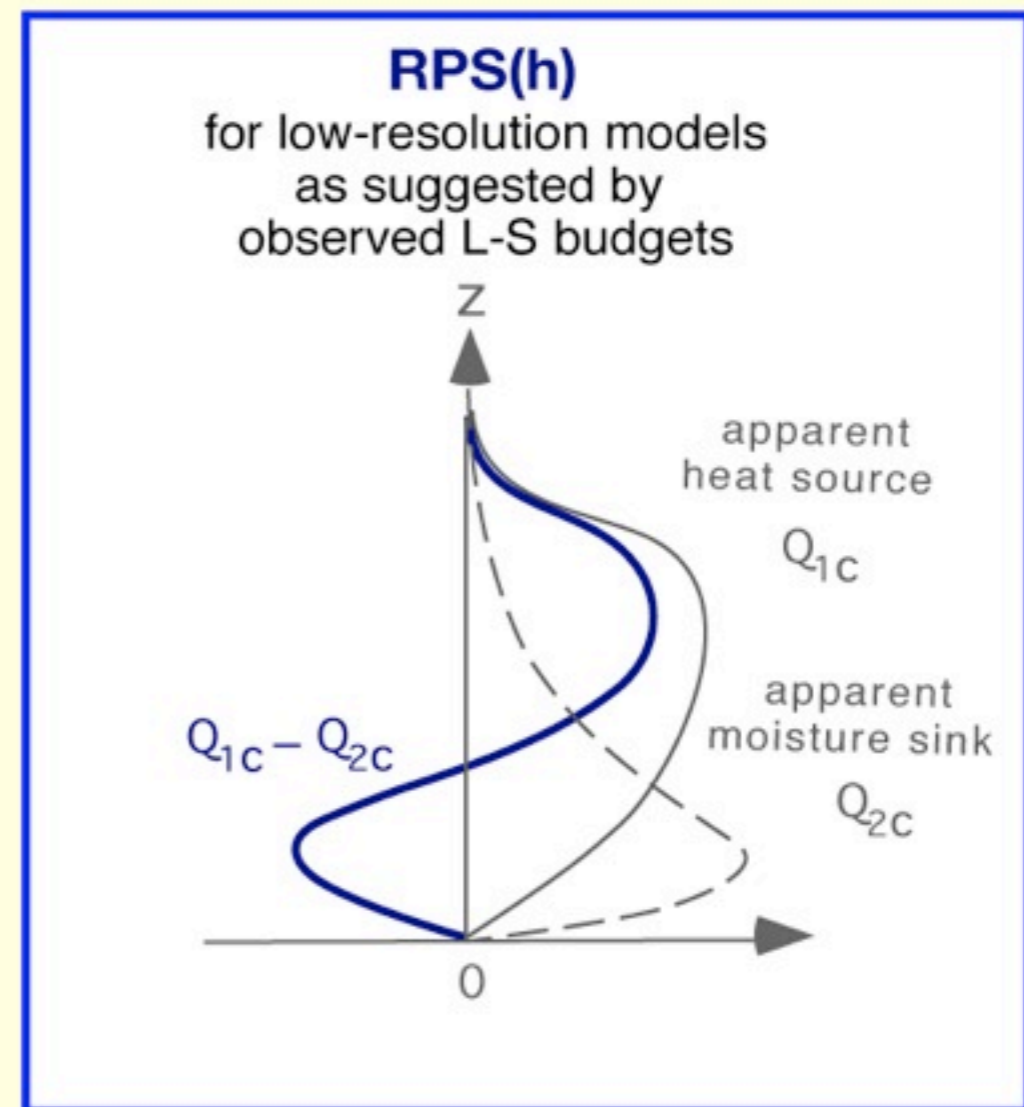
Typical vertical profiles of the apparent moist static energy source due to convective activity

Fine scale

Average over a larger area

Any space/time/ensemble averages of the profiles in the left panel do NOT give the profile in the right panel.

In summary:
Three problems with conventional parameterizations at high resolution:

- The sample size is too small to enable a statistical treatment.

- The "resolved-scale forcing" varies too quickly to allow quasi-equilibrium.

- Convective transports become less important, and microphysics dominates.

Increasing resolution makes these problems worse.

- **Smaller grid cells contain fewer clouds.**

- **Smaller weather systems, resolved by finer grids, have shorter time scales.**

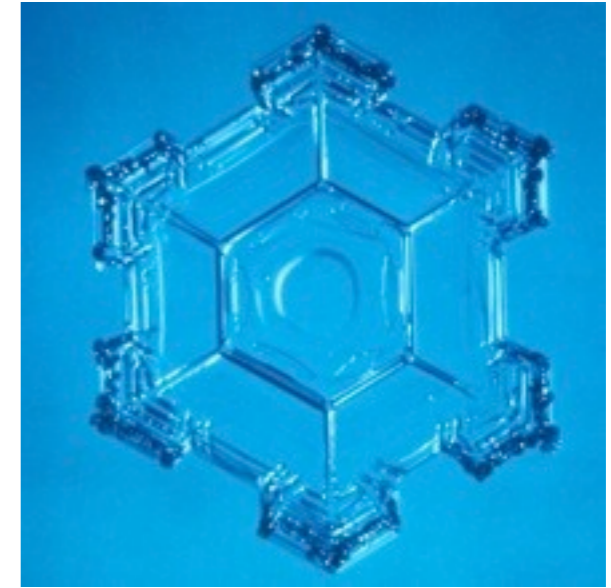# Parameterize less.

Global circulation

Cloud-scale &mesoscale processes

Radiation, Microphysics, Turbulence
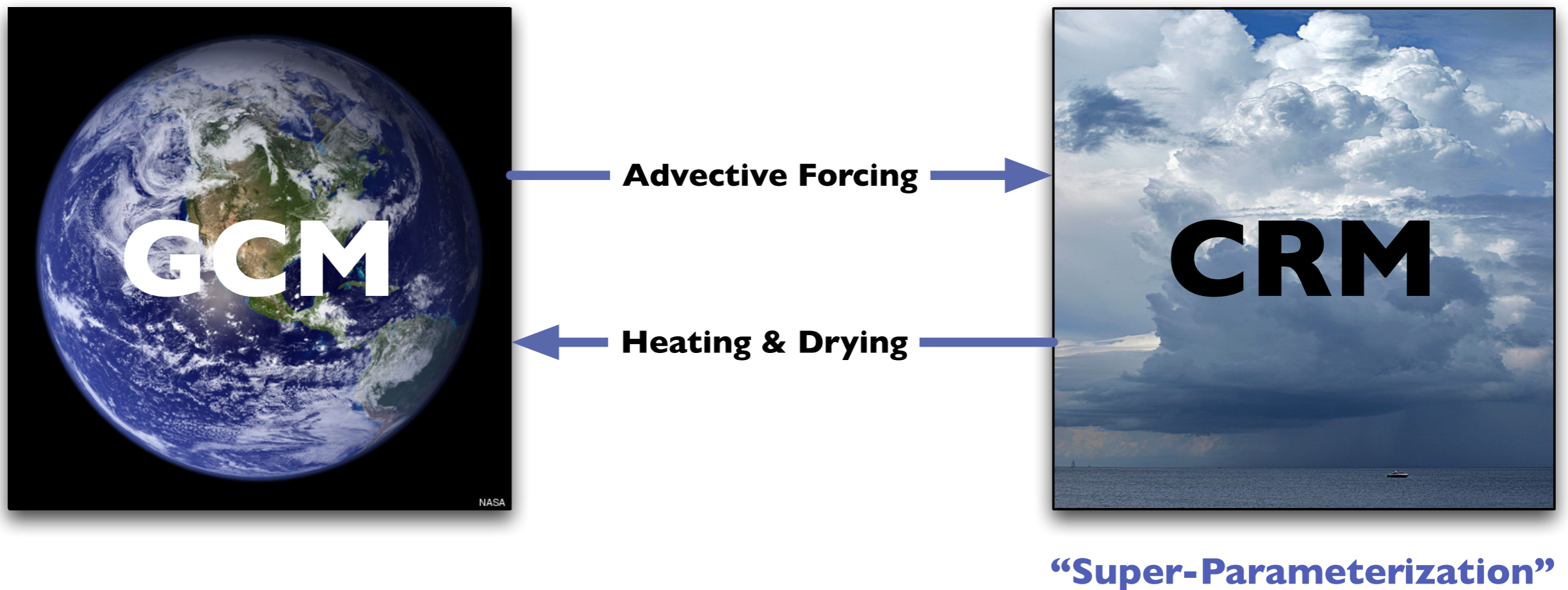
Parameterized

Three Ways to Use Cloud-Resolving Models To Improve Global Models

- **Test parameterizations and suggest ideas**

- **Replace parameterizations**

- **Become the global model**

To save time, and because NICAM is here, I won't talk about GCRMs.

Multiscale Modeling Framework

GCM

Advective Forcing →

← Heating & Drying

CRM

"Super-Parameterization"
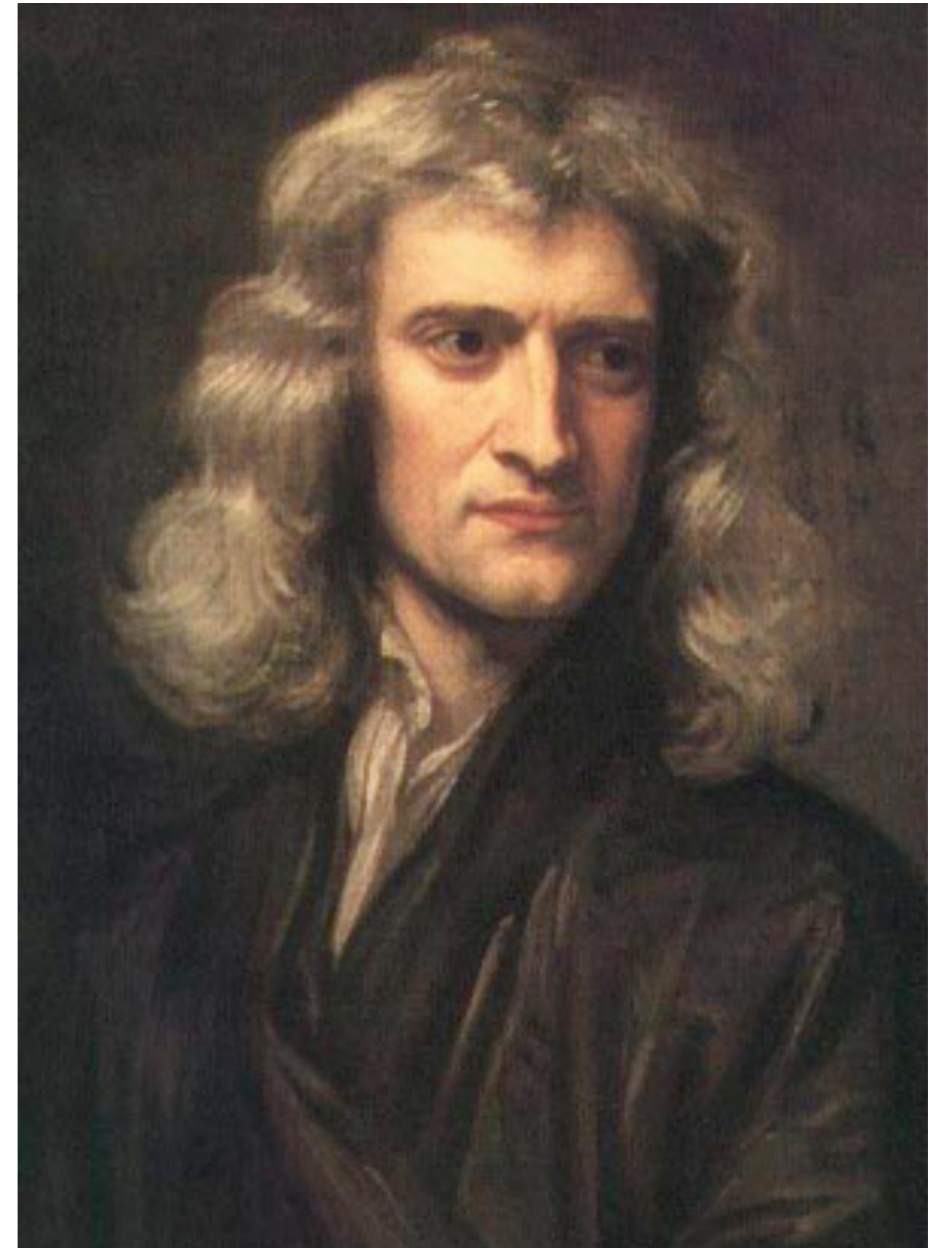
- **Each CRM runs continuously.**

- **The CRMs do not communicate with each other.**

- **The width of the CRM domain is not tied to the GCM grid size.**
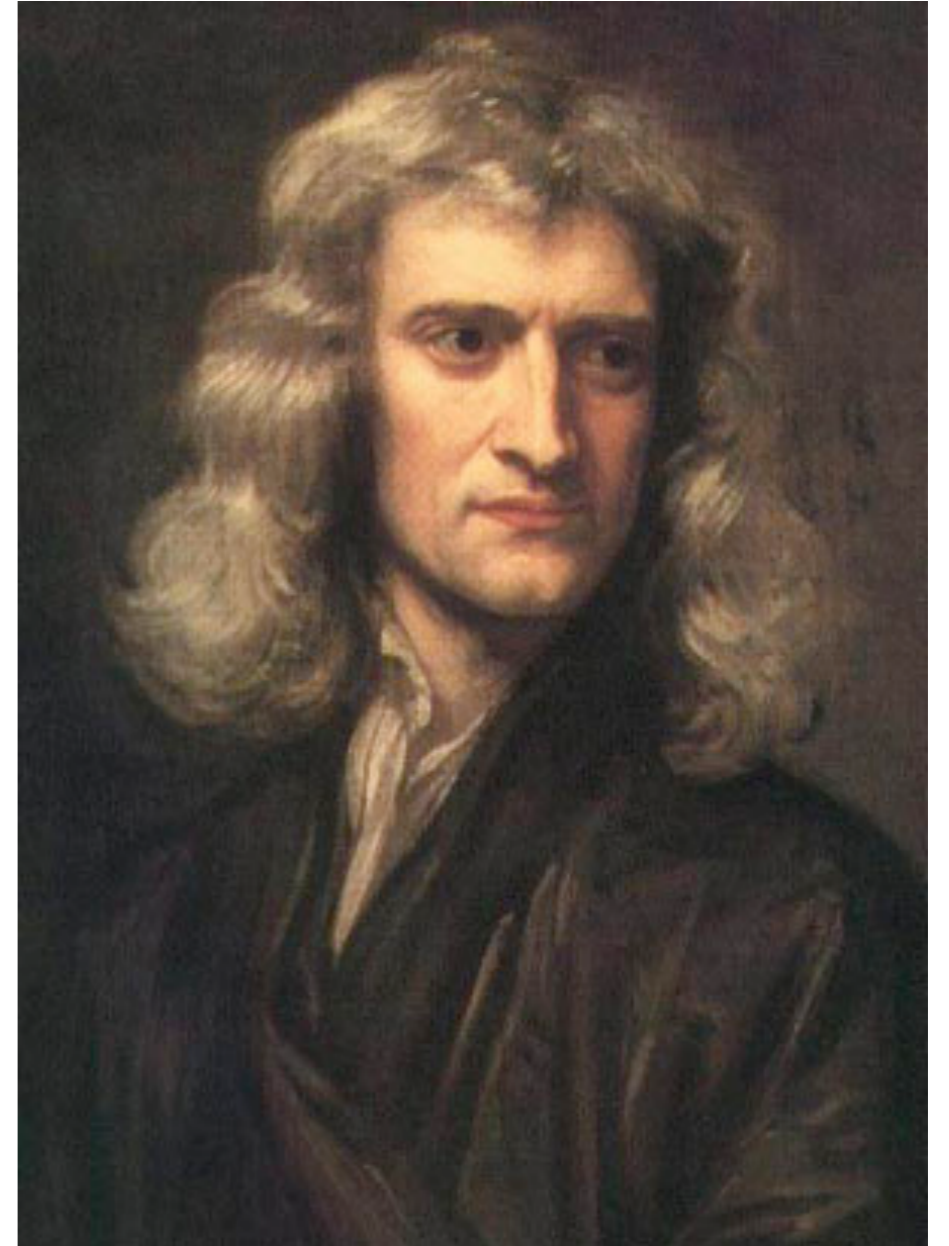
What's different?

- **The equation of motion**
    - **No closure assumptions**
    - **No triggers**
    - **Mesoscale organization**

What's different?

- **The equation of motion**
  - **No closure assumptions**
  - **No triggers**
  - **Mesoscale organization**
- **CRM memory**
  - **Delay in convective response**
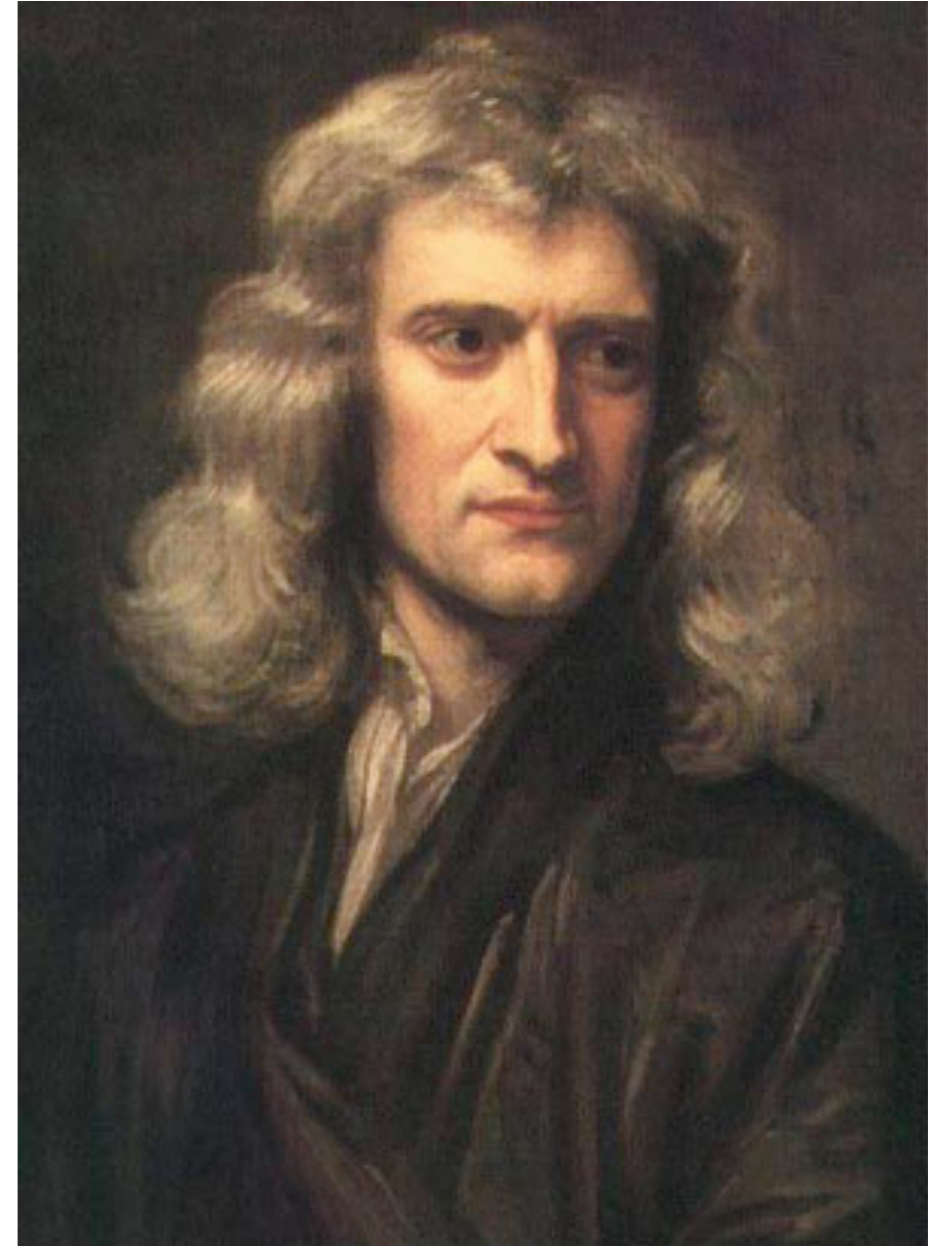 - **Sensitive dependence on initial conditions**

What's different?

- **The equation of motion**
  - **No closure assumptions**
  - **No triggers**
  - **Mesoscale organization**
- **CRM memory**
  - **Delay in convective response**
  - **Sensitive dependence on initial conditions**
- **Almost embarrassingly parallel**

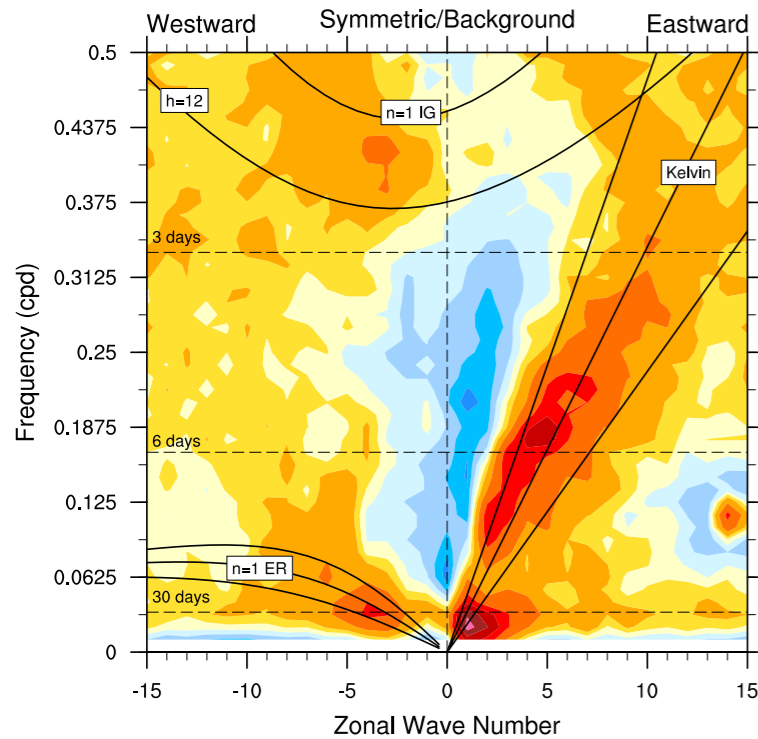# The MMF produces realistic variability on a wide range of time scales.

- Diurnal cycle (especially papers by Mike Pritchard et al.)

- MJO

- Monsoon fluctuations

- ENSO

http://www.cmmap.org/research/pubs-mmf.html

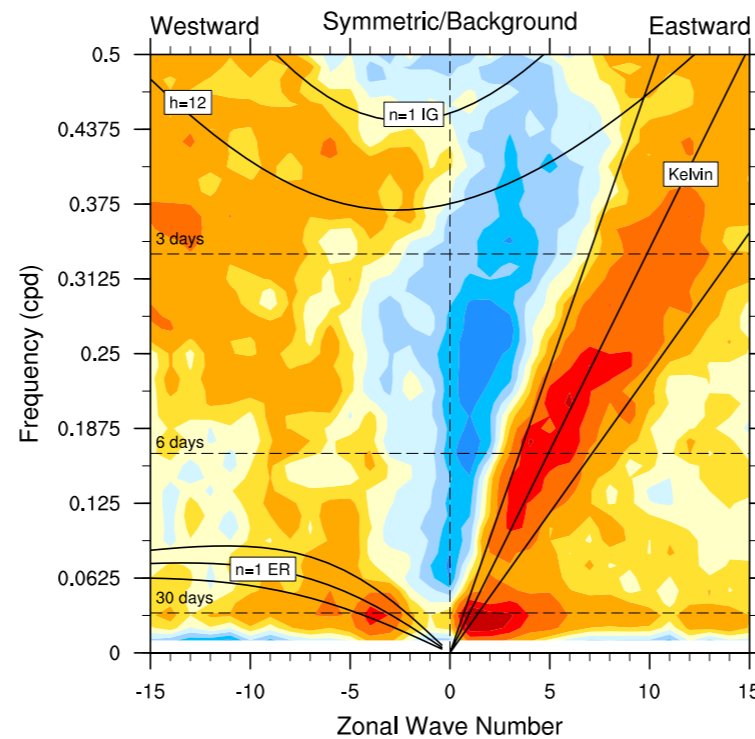# Symmetric Equatorial Waves

- **More robust MJO spectral signal in SP-CCSM**

- **Slower and more robust Kelvin wave behavior in SP-CCSM**
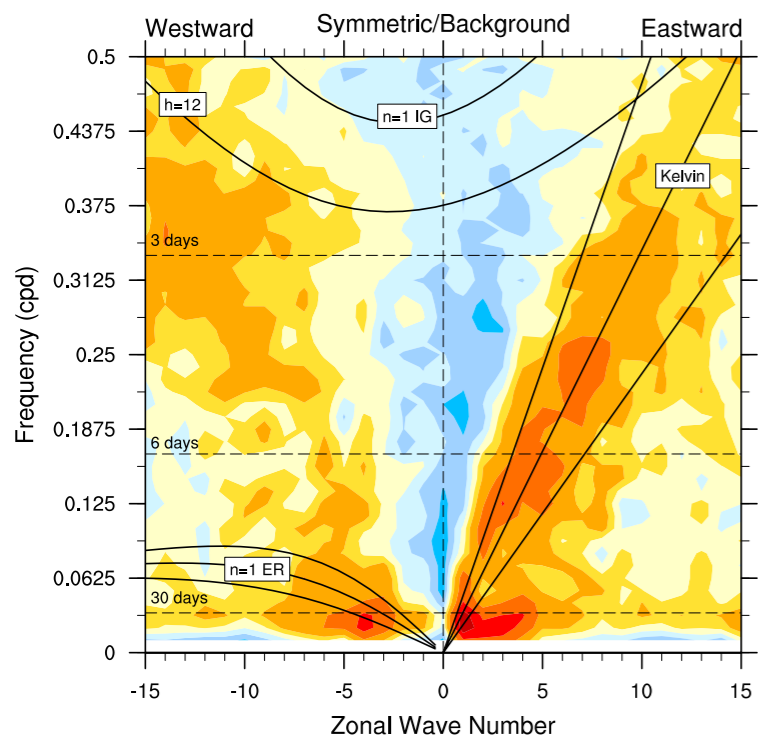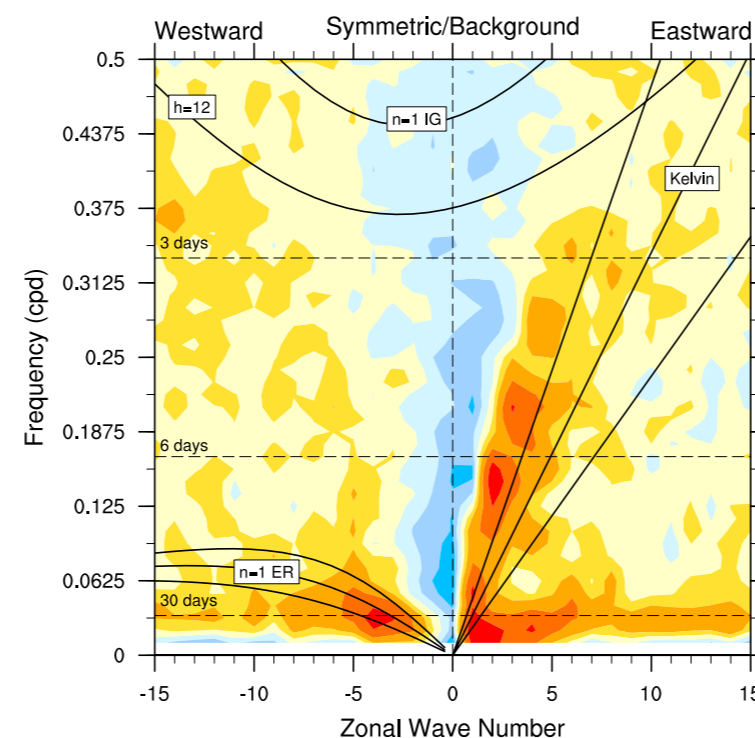
Eastward-propagating precipitation

5N-25N, eastward wave #s 1-6, periods 24-70 days

Variance BSIO, May-Oct

GPCP
CCSM
SpCCSM
SpCAM (dashed)
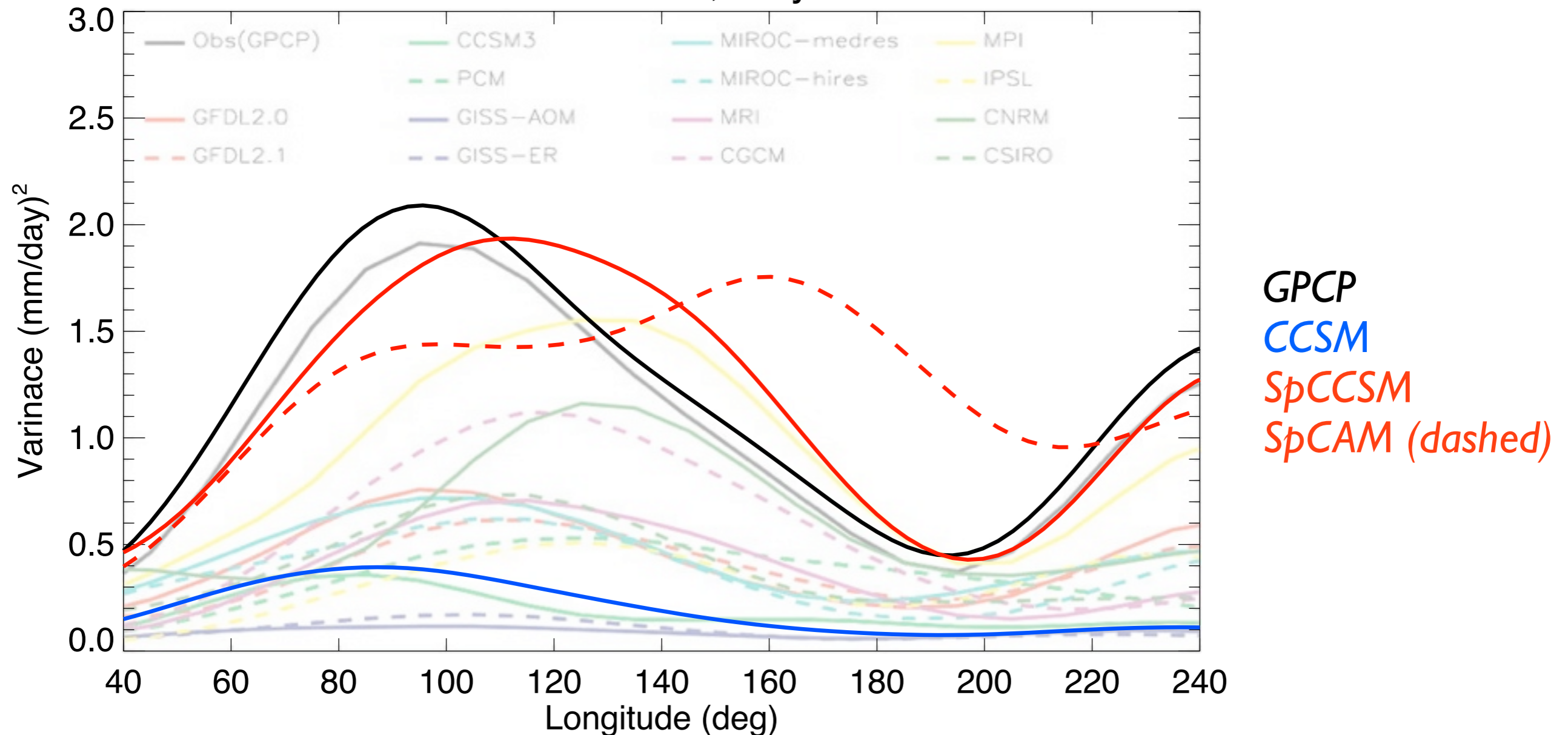
Base figure from Lin et al. 2008

Anti-Symmetric Equatorial Waves

Slide from Charlotte DeMott
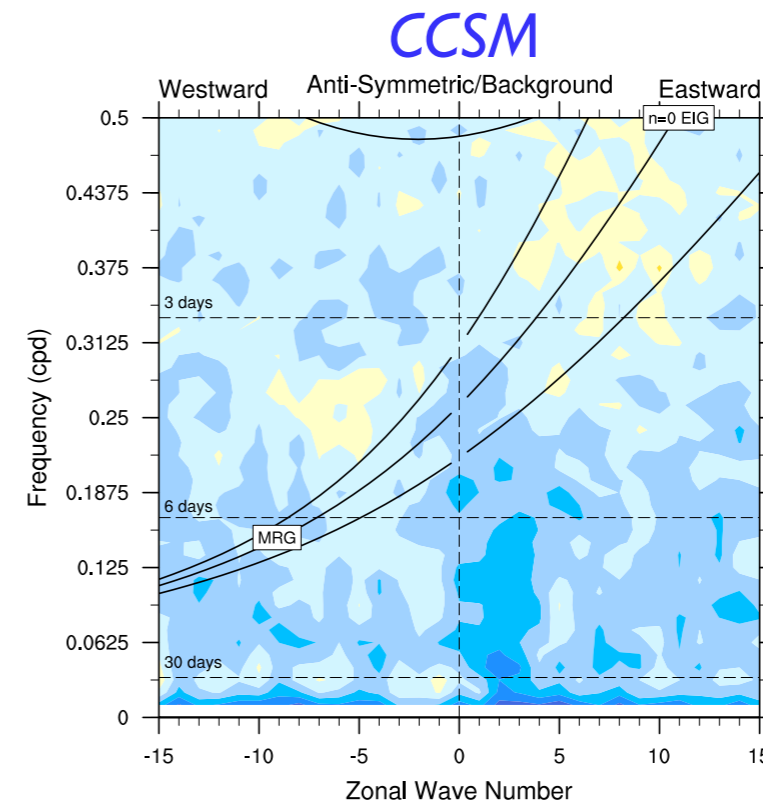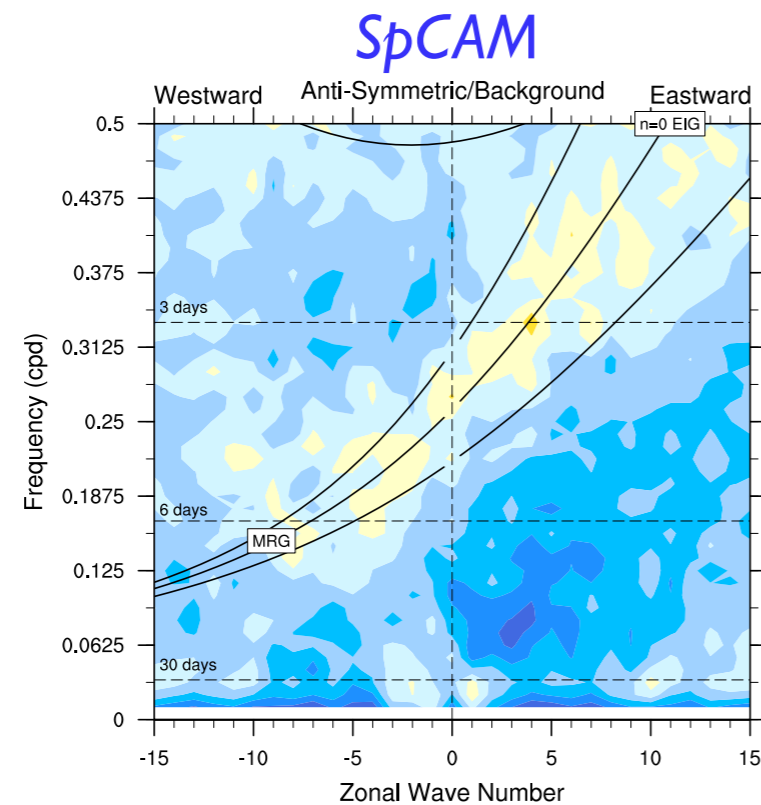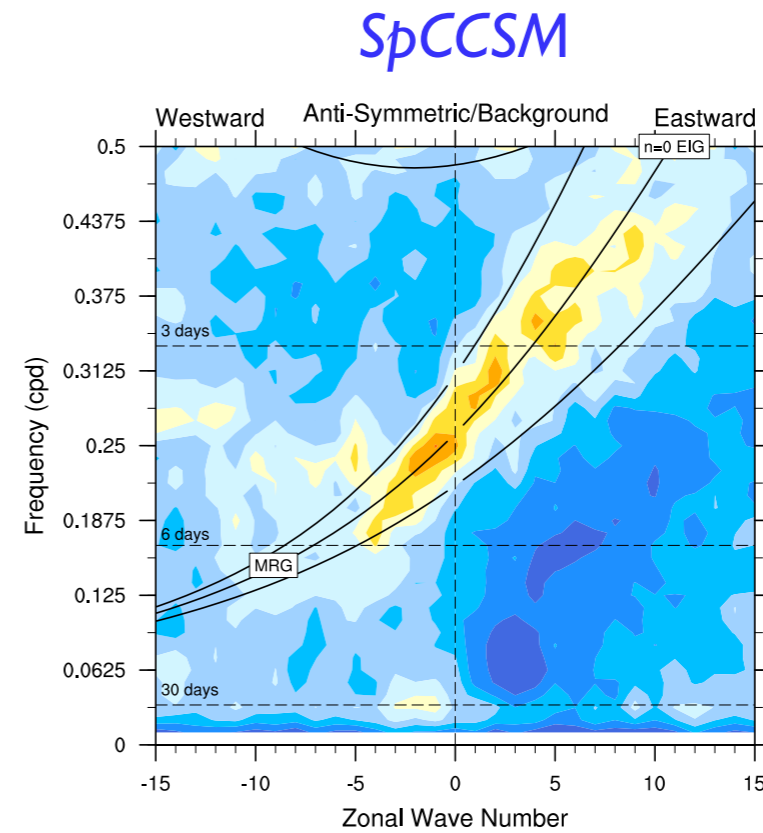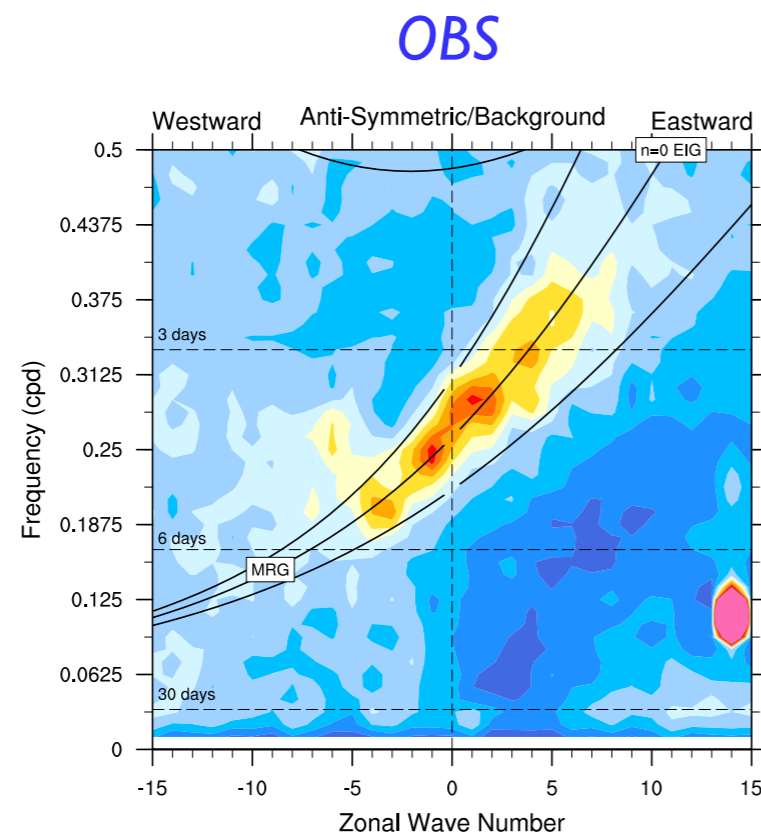
Indian Ocean meridional composite by MJO PC1+PC2 phase
(2 cycles shown)
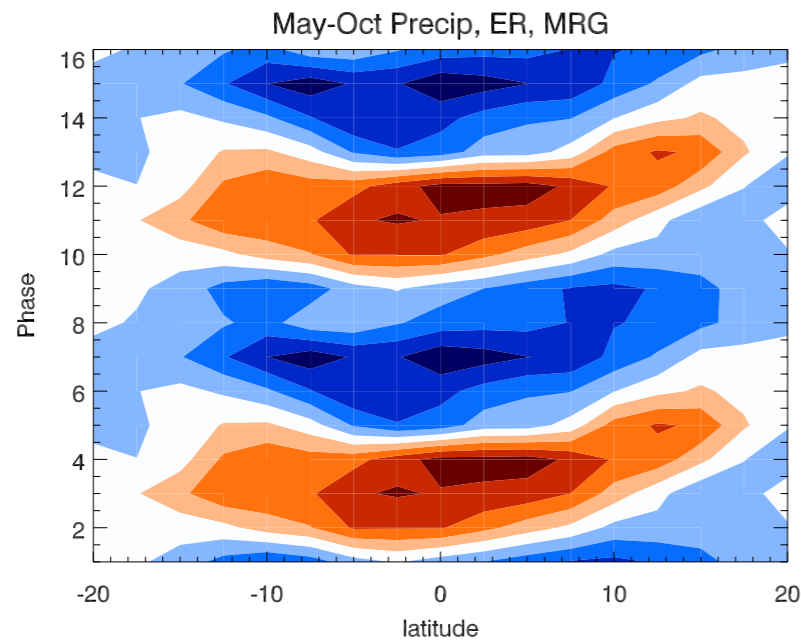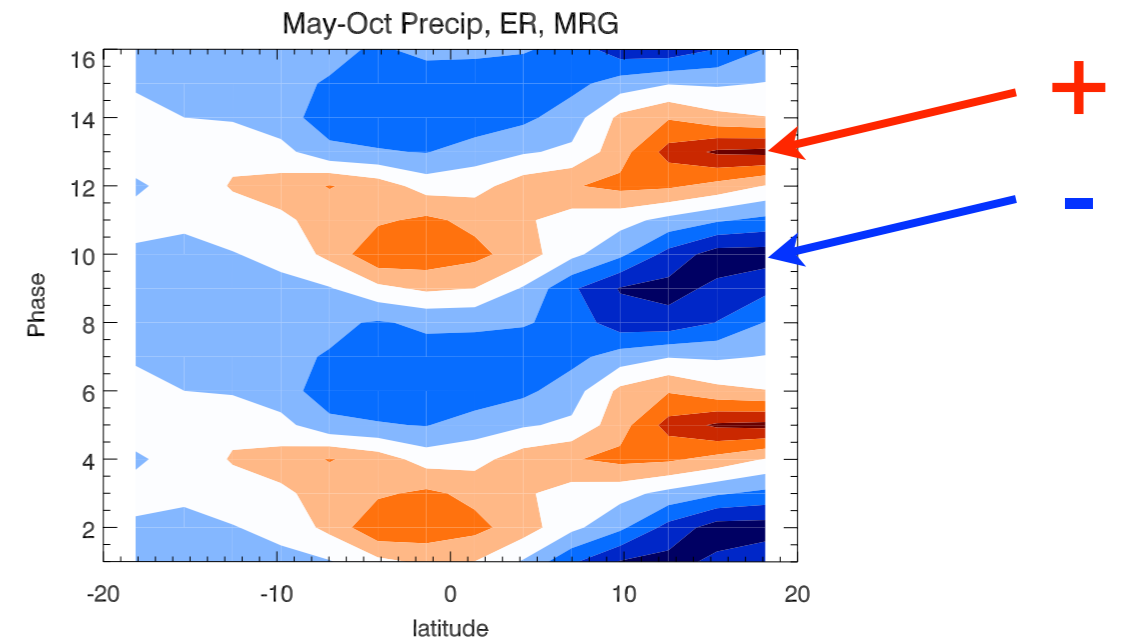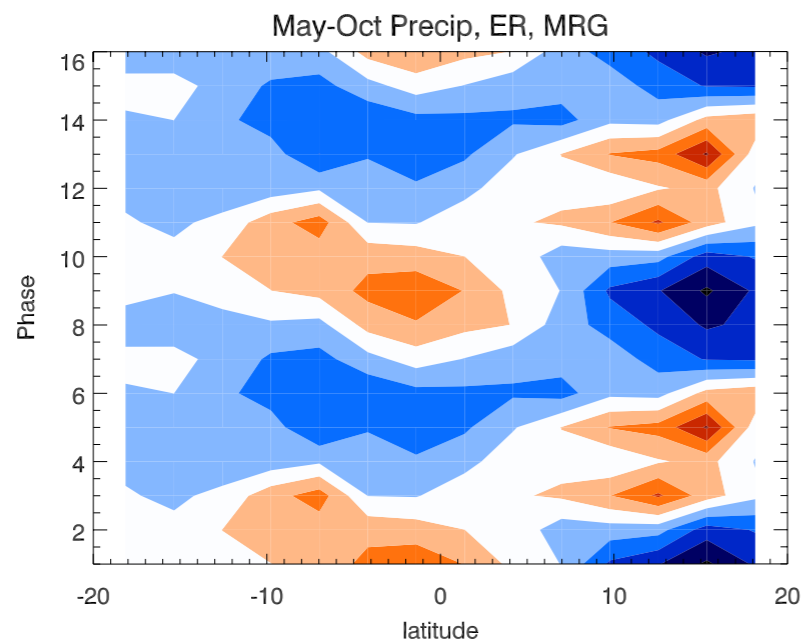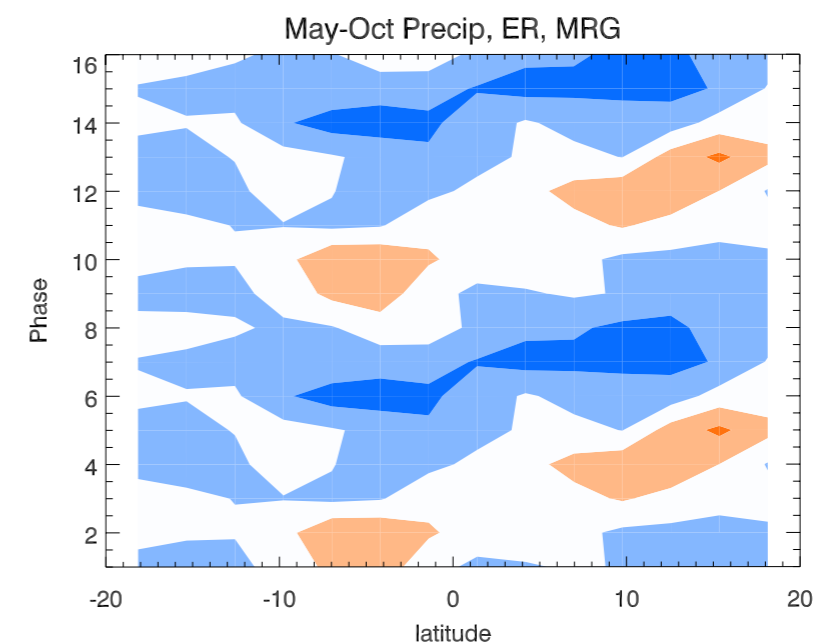
Precip' (red= positive anomaly)

Different input, different output

```
┌─────────┐        ┌──────────────────┐        ┌─────────┐
│  Input  │ ─────► │  Parameterization │ ─────► │ Output  │
└─────────┘        └──────────────────┘        └─────────┘
```

Different input, different output

Input → Parameterization → Output
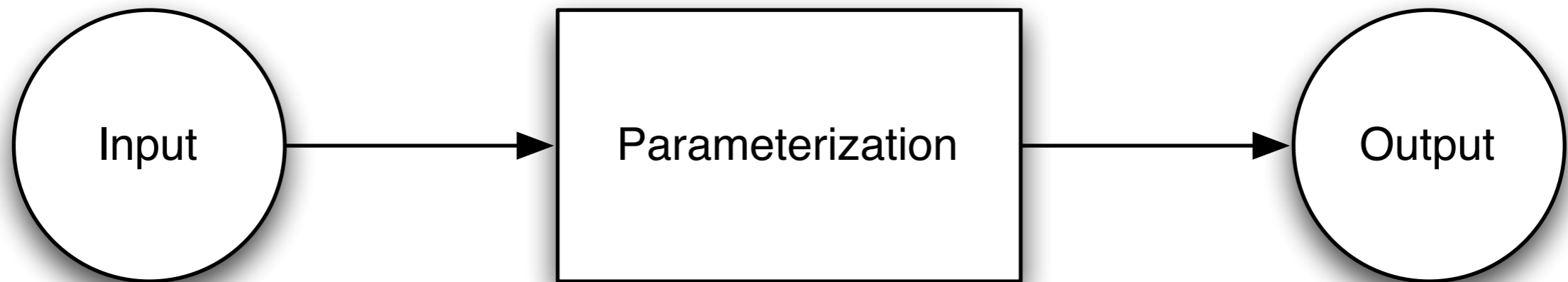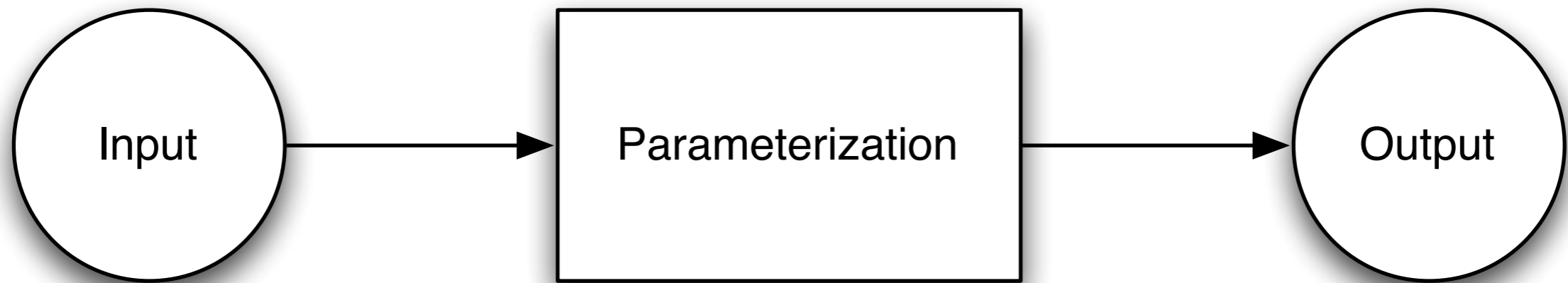
⬡ **Turbulence**

Different input, different output
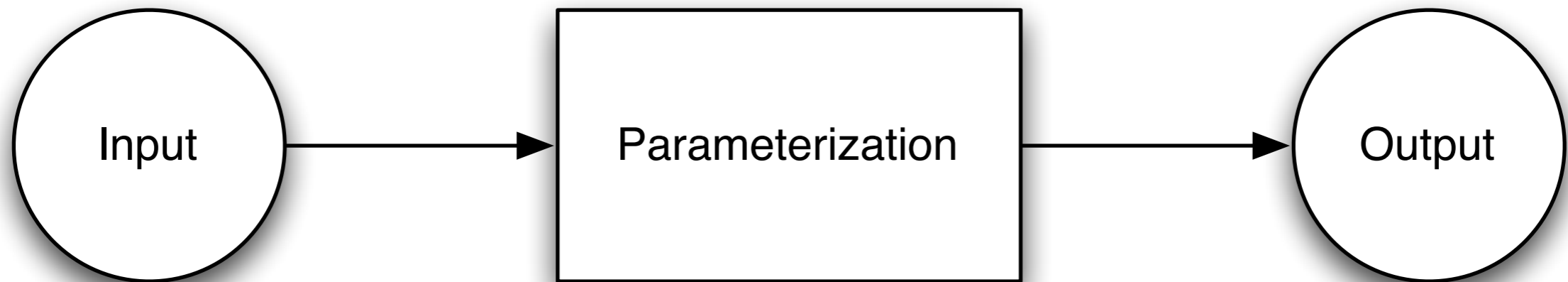
- **Turbulence**

- **Microphysics, including aerosols**

Black carbon concentrations in the polar regions
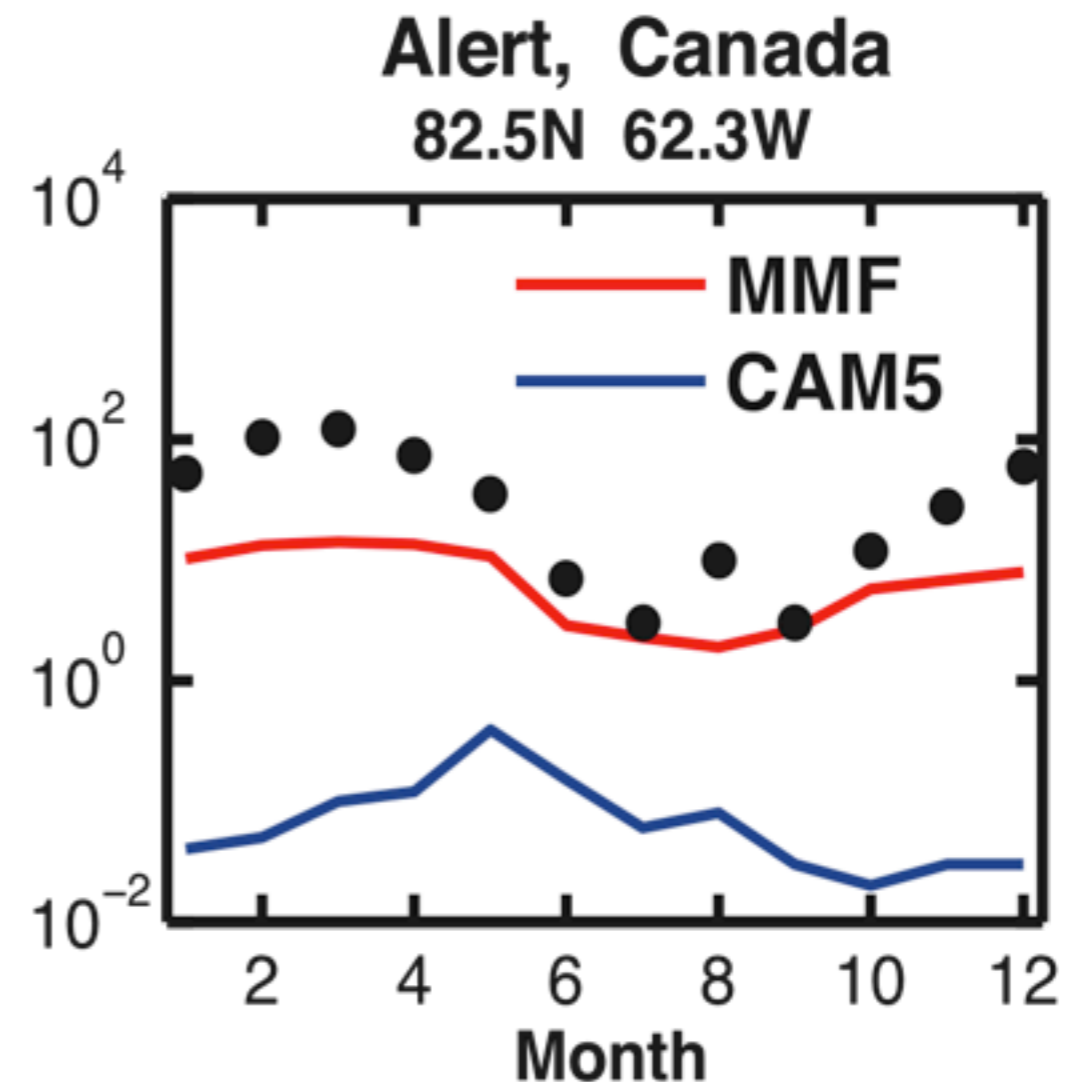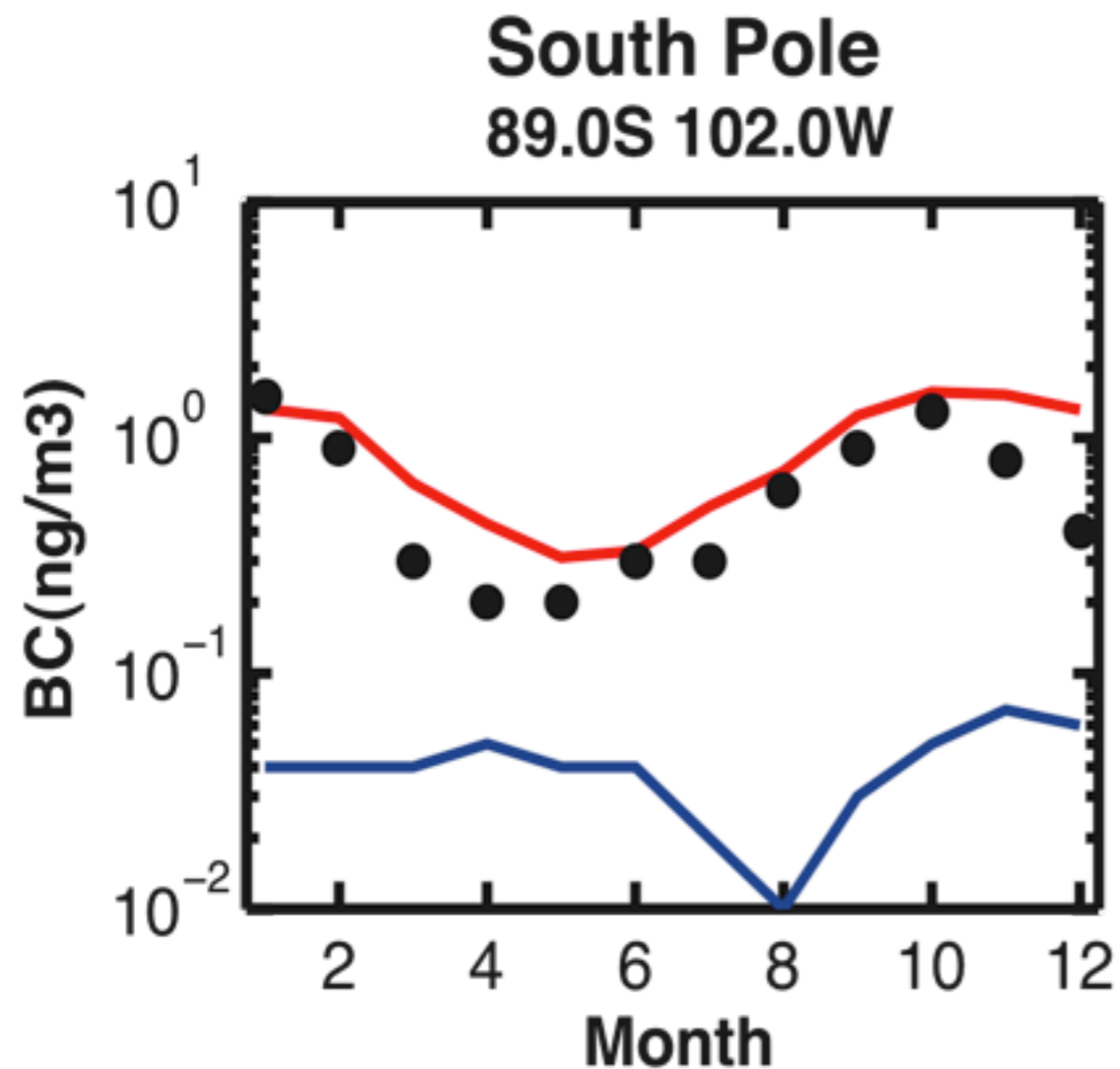
The two models share the same dynamical core and aerosol parameterization.

Only the parameterized aerosol transport is different.

Slide from Minghuai Wang of PNNL

"Scale-Aware" Parameterizations?

🛑 **Equations and code unchanged as grid spacing varies from 100 km to 1 km**

🛑 **Ensemble of clouds to the interior of a single cloud**

A "scale-aware" parameterization of deep convection has been proposed by Akio Arakawa and colleagues.

Arakawa, A., J.-H. Jung, and C.-M. Wu, 2011: Toward unification of the multiscale modeling of the atmosphere. *Atmos. Chem. Phys.*, **11**, 3731-3742.

"THE UNIFIED PARAMETERIZATION"

An attempt to unify parameterizations in GCMs and CRMs

Generalization, not replacement, of conventional cumulus parameterization

to include its transition to an explicit simulation of moist convection.

Prerequisite :

The host model can become a CRM when the resolution is sufficiently high.

Slide from Akio Arakawa

OPENING A ROUTE FOR UNIFIED PARAMETERIZATION

σ : the fractional area covered by *all* convective clouds

– a measure of fractional population of clouds

Conventional parameterizations assume $\sigma \ll 1$, either explicitly or implicitly.

$\sigma \ll 1$

subgrid-scale circulation

grid-scale circulation
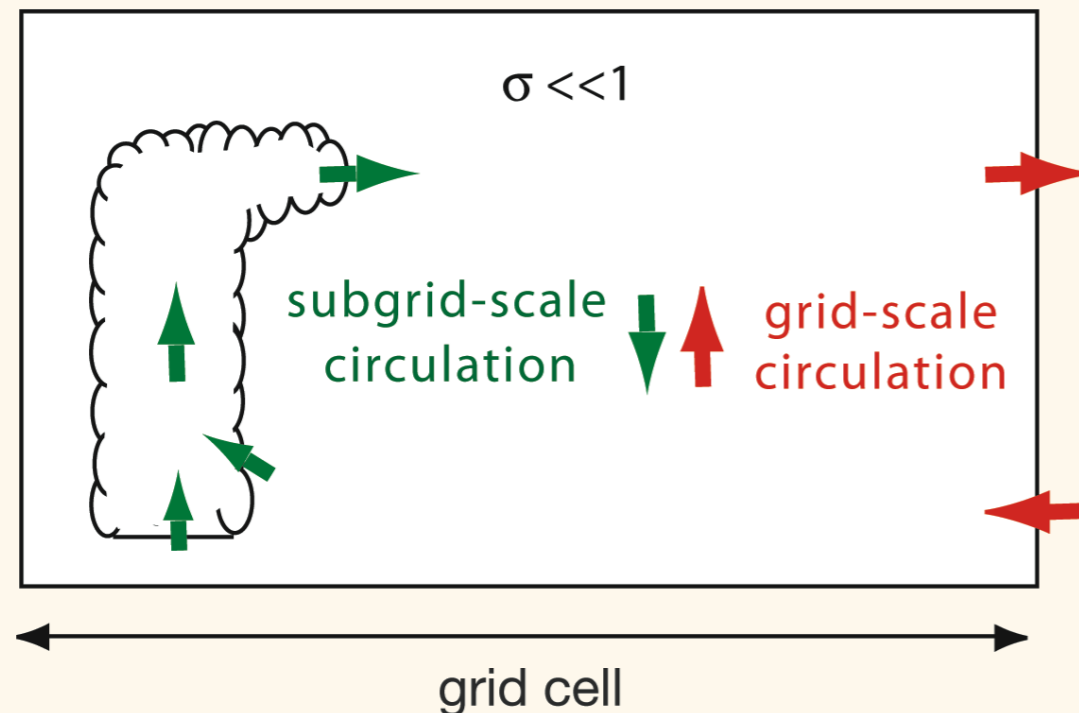
grid cell

With high resolutions, however, cloud may occupy the entire grid cell.

$\sigma \sim 1$ $\sigma = 0$ $\sigma = 0$ $\sigma = 0$ $\sigma = 0$

grid-scale circulation

grid cell
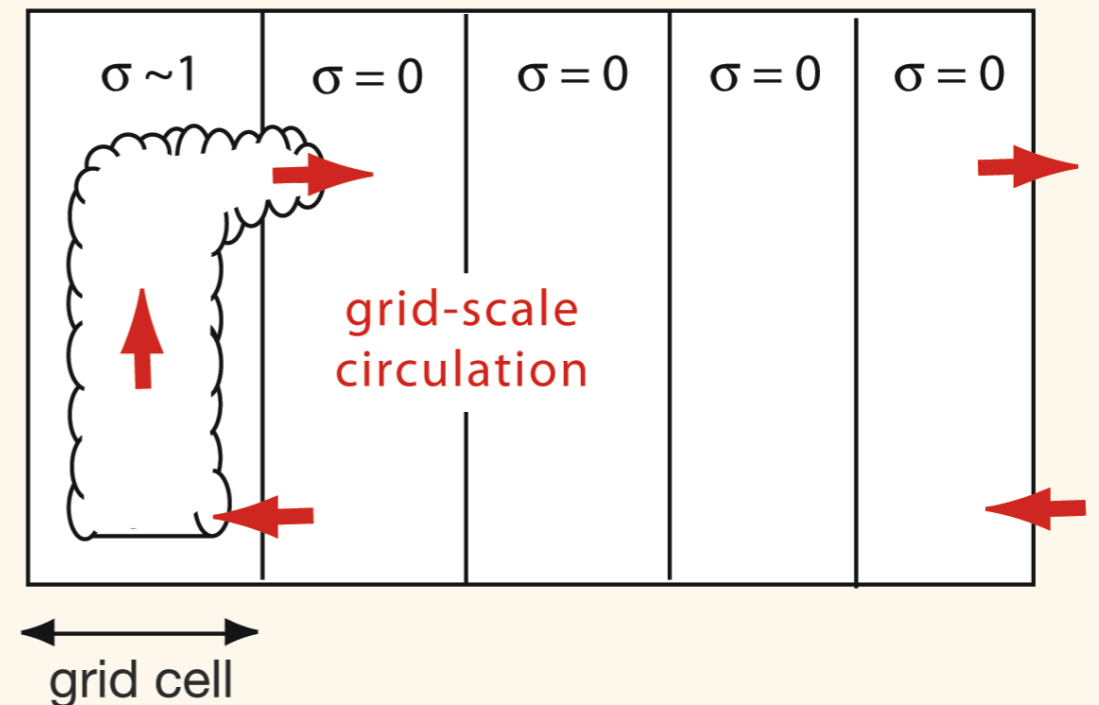
To open a route, the assumption of $\sigma \ll 1$ must be eliminated.

Slide from Akio Arakawa

Derivation I

For a homogeneous cloud in a homogeneous environment, we can derive

$$\overline{w\psi} - \overline{w}\,\overline{\psi} = \left(\frac{\sigma}{1-\sigma}\right)\left(w_c - \overline{w}\right)\left(\psi_c - \overline{\psi}\right) \quad .$$

For convergence, we need

$$\lim_{\sigma \to 1} w_c = \overline{w} \qquad \text{and} \qquad \lim_{\sigma \to 1} \psi_c = \overline{\psi} \quad .$$

This leads us to guess that

$$\left(w_c - \overline{w}\right)\left(\psi_c - \overline{\psi}\right) = \left(1-\sigma\right)^2 \left[\left(w_c - \overline{w}\right)\left(\psi_c - \overline{\psi}\right)\right]^* \quad ,$$

where the star denotes a limiting value as $\sigma \to 0$.

This limiting value can be obtained using a plume model. Note that we will need a vertical velocity equation for the plume.

Arakawa, A., J.-H. Jung, and C.-M. Wu, 2011: Toward unification of the multiscale modeling of the atmosphere. *Atmos. Chem. Phys.*, **11**, 3731-3742.

Derivation 2

Substituting (3) into (1), we obtain

$$\overline{w\psi} - \overline{w}\,\overline{\psi} = \sigma(1-\sigma)\left[\left(w_c - \overline{w}\right)\left(\psi_c - \overline{\psi}\right)\right]^* \quad .$$

Let

$$\left(\overline{w\psi} - \overline{w}\,\overline{\psi}\right)_{\mathrm{adj}}$$

denote the flux required to achieve a fully adjusted state, i.e., quasi-equilibrium. This flux can be computed from a conventional parameterization. *For consistency*, we require that

$$\left(\overline{w\psi} - \overline{w}\,\overline{\psi}\right)_{\mathrm{adj}} = \left(\frac{\sigma}{1-\sigma}\right)\left[\left(w_c - \overline{w}\right)\left(\psi_c - \overline{\psi}\right)\right]^* \quad .$$

Solving for σ, we obtain

$$\sigma = \frac{\left(\overline{w\psi} - \overline{w}\,\overline{\psi}\right)_{\mathrm{adj}}}{\left(\overline{w\psi} - \overline{w}\,\overline{\psi}\right)_{\mathrm{adj}} + \left[\left(w_c - \overline{w}\right)\left(\psi_c - \overline{\psi}\right)\right]^*} \quad .$$

That's it. The "Unified Parameterization" requires only minor changes to a model that uses a conventional parameterization.

Arakawa, A., J.-H. Jung, and C.-M. Wu, 2011: Toward unification of the multiscale modeling of the atmosphere. *Atmos. Chem. Phys*., **11**, 3731-3742.

ANALYSIS OF GRID-SIZE DEPENDENT STATISTICS OF THE CRM DATA

The original domain is divided into sub-domains with the same size.
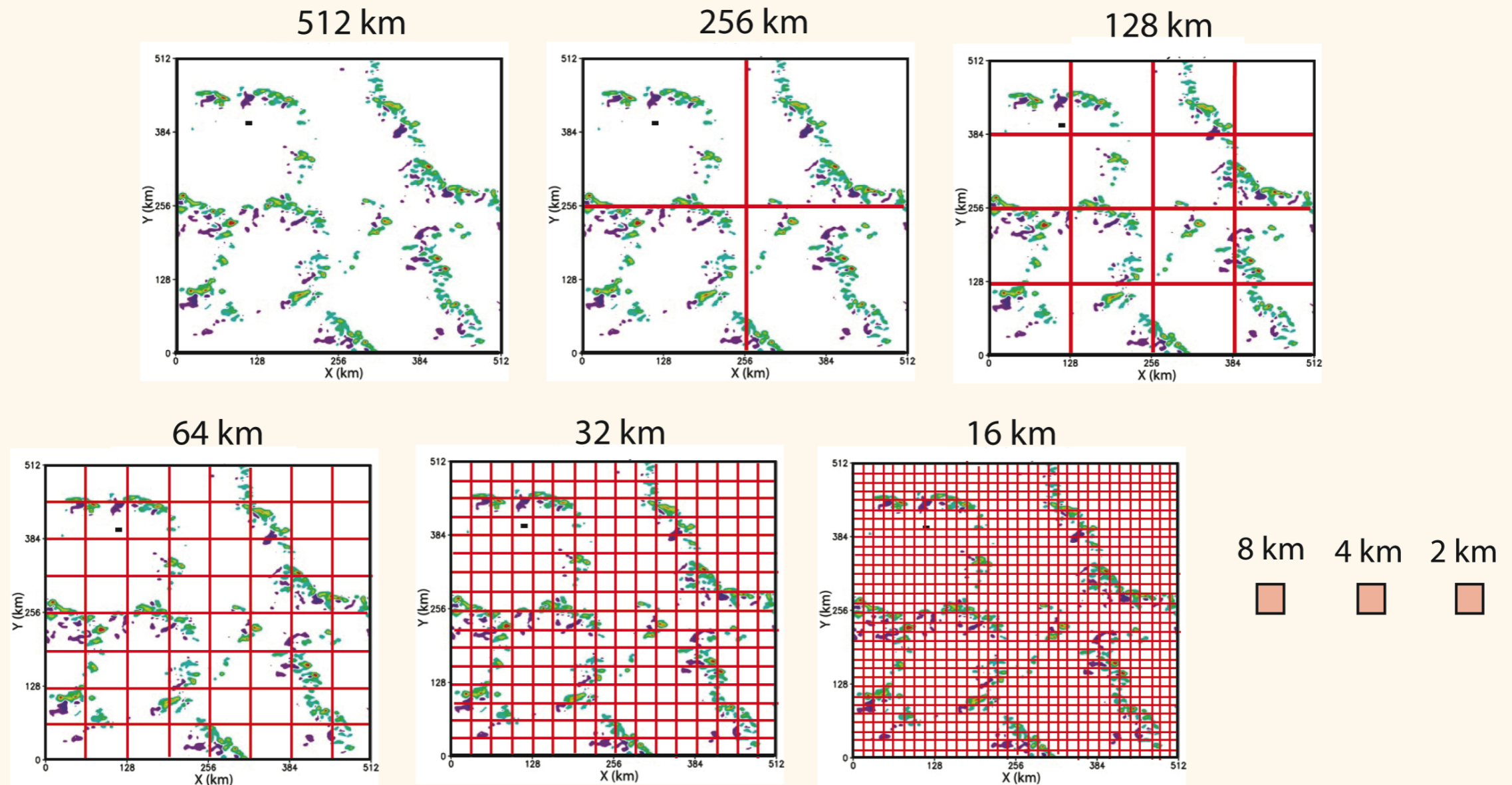
These sub-domains are assumed to represent grid cells of a GCM.

$$\overline{w\psi} - \overline{w}\,\overline{\psi} = \sigma(1-\sigma)\left[\left(w_c - \overline{w}\right)\left(\psi_c - \overline{\psi}\right)\right]^*$$
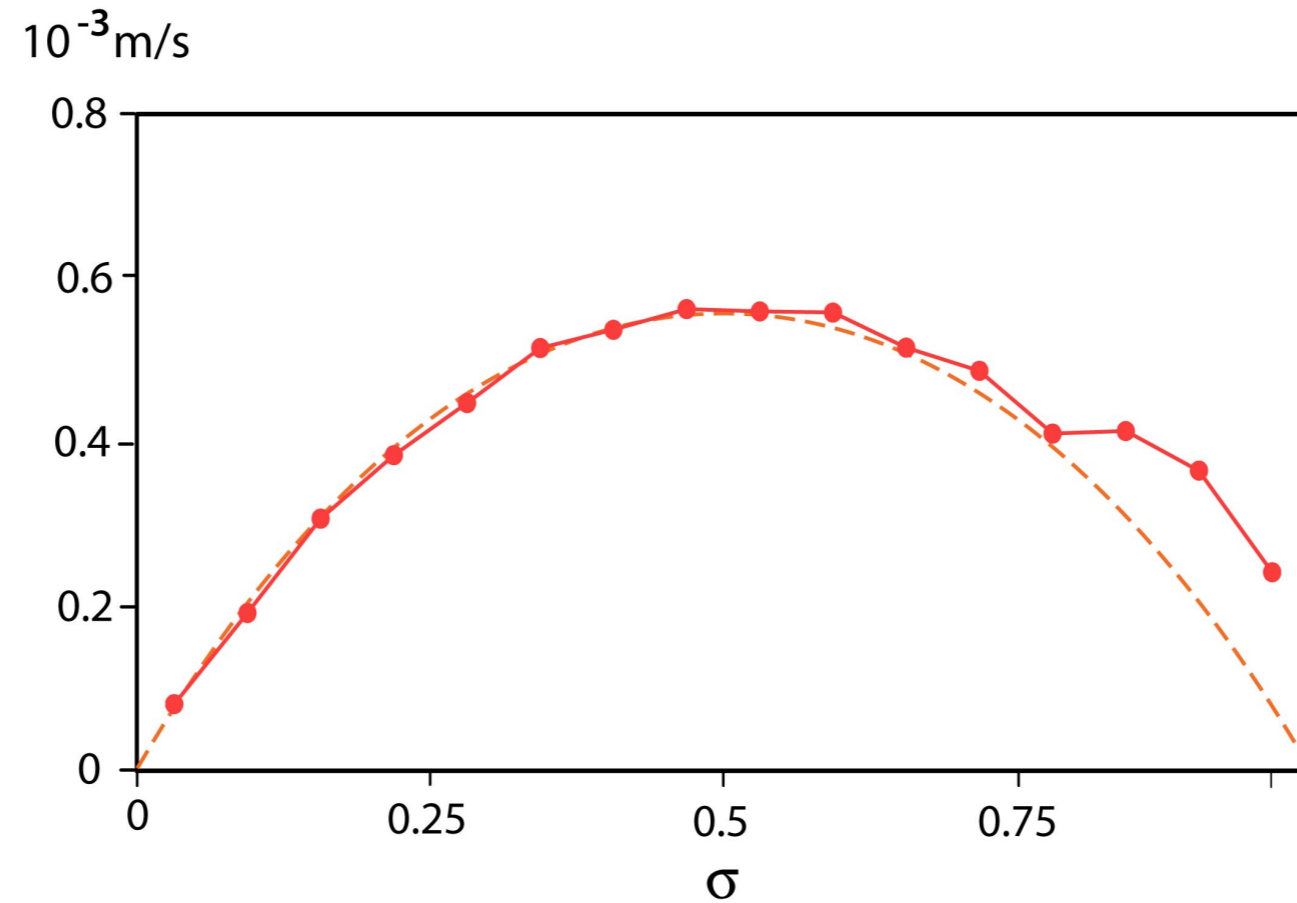
Fig. 9. The σ-dependence of the diagnosed $(\overline{wq} - \overline{w}\,\overline{q})$ averaged over all sub-domains that share σ in the same sub-range for the case in bold face in Table 1a. The dashed curve shows $\sigma(1-\sigma)$ multiplied by a constant chosen for the best fit to the dots for small and medium values of σ.

Arakawa, A., J.-H. Jung, and C.-M. Wu, 2011: Toward unification of the multiscale modeling of the atmosphere. *Atmos. Chem. Phys.*, **11**, 3731-3742.

Arakawa, A., J.-H. Jung, and C.-M. Wu, 2011:
Toward unification of the multiscale modeling of the atmosphere.
Atmos. Chem. Phys., **11**, 3731-3742.

Three Ways to Use Cloud-Resolving Models To Improve Global Models

- **Test parameterizations and suggest ideas**

- **Replace parameterizations** *(second-generation MMF coming soon)*

- **Become the global model**